Borexino: A Multi-Purpose Detector for the Study of Solar and Terrestrial Neutrinos

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University of Chicago HEP Seminar
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Solar Neutrino Production

p-p Solar Fusion Chain

$p + p \rightarrow {}^{2}H + e^{+} + \nu_e$ $\quad$ $p + e^{-} + p \rightarrow {}^{2}H + \nu_e$

${}^{2}H + p \rightarrow {}^{3}He + \gamma$

${}^{3}He + {}^{3}He \rightarrow {}^{4}He + 2\,p$ $\quad$ ${}^{3}He + p \rightarrow {}^{4}He + e^{+} + \nu_e$

${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$

${}^{7}Be + e^{-} \rightarrow {}^{7}Li + \gamma + \nu_e$ $\quad$ ${}^{7}Be + p \rightarrow {}^{8}B + \gamma$

${}^{7}Li + p \rightarrow \alpha + \alpha$ $\quad$ ${}^{8}B \rightarrow 2\,\alpha + e^{+} + \nu_e$

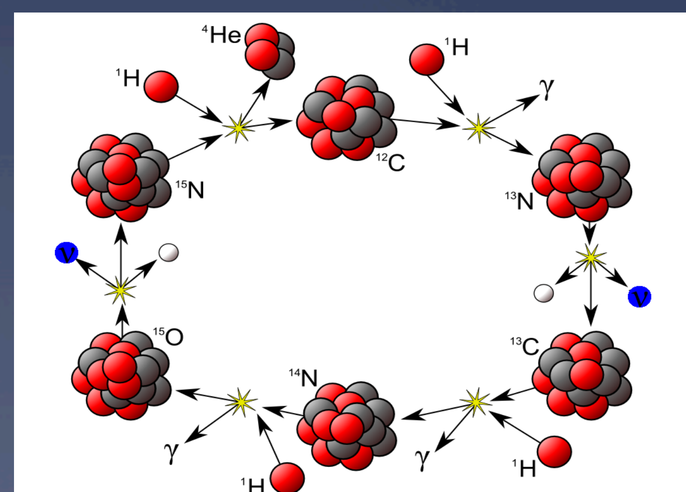
CNO Solar Fusion Cycle

${}^{12}C + p \rightarrow {}^{13}N + \gamma$ $\quad$ ${}^{13}N \rightarrow {}^{13}C + e^{+} + \nu_e$

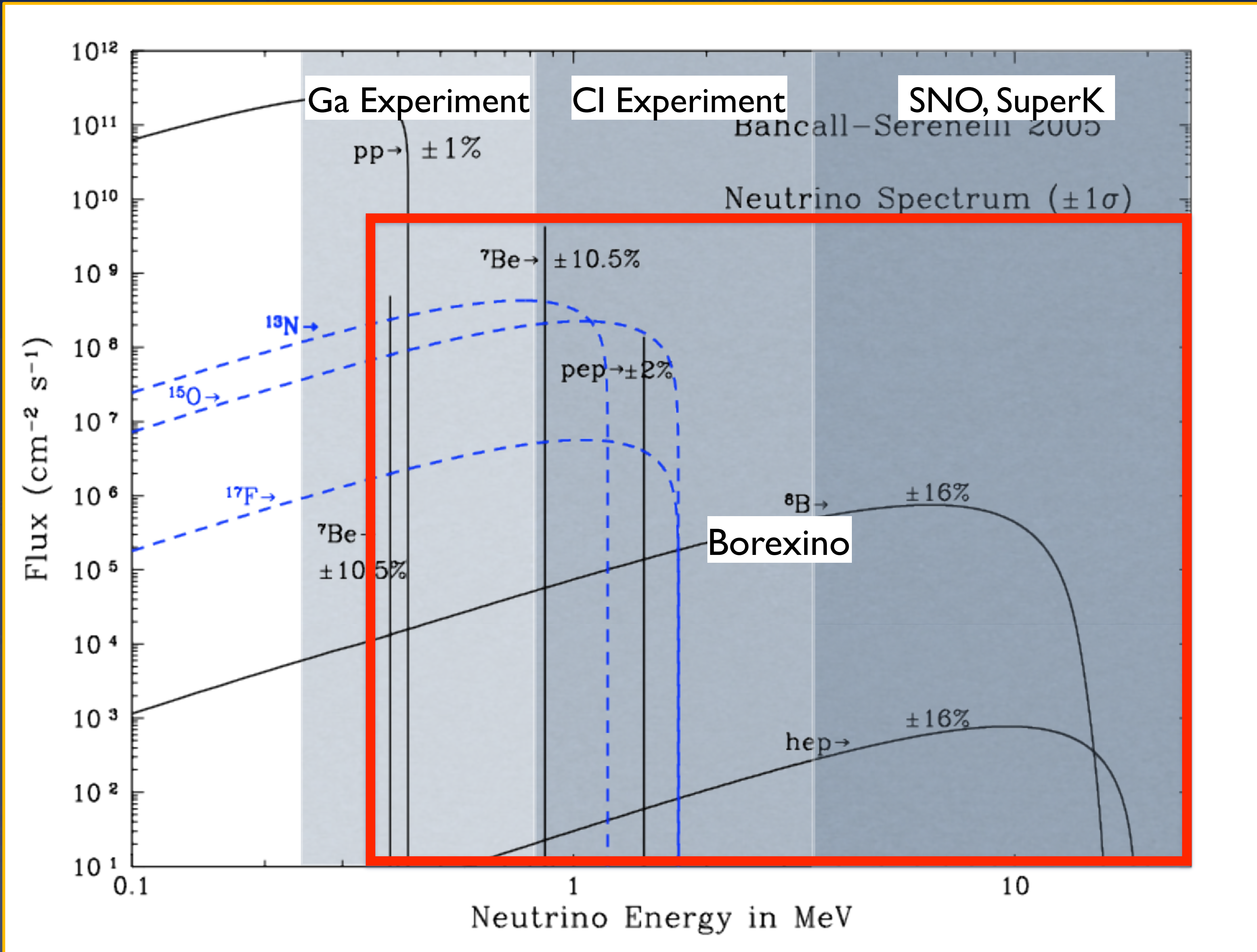
${}^{13}C + p \rightarrow {}^{14}N + \gamma$

${}^{14}N + p \rightarrow {}^{15}O + \gamma$ $\quad$ ${}^{15}O \rightarrow {}^{15}N + e^{+} + \nu_e$

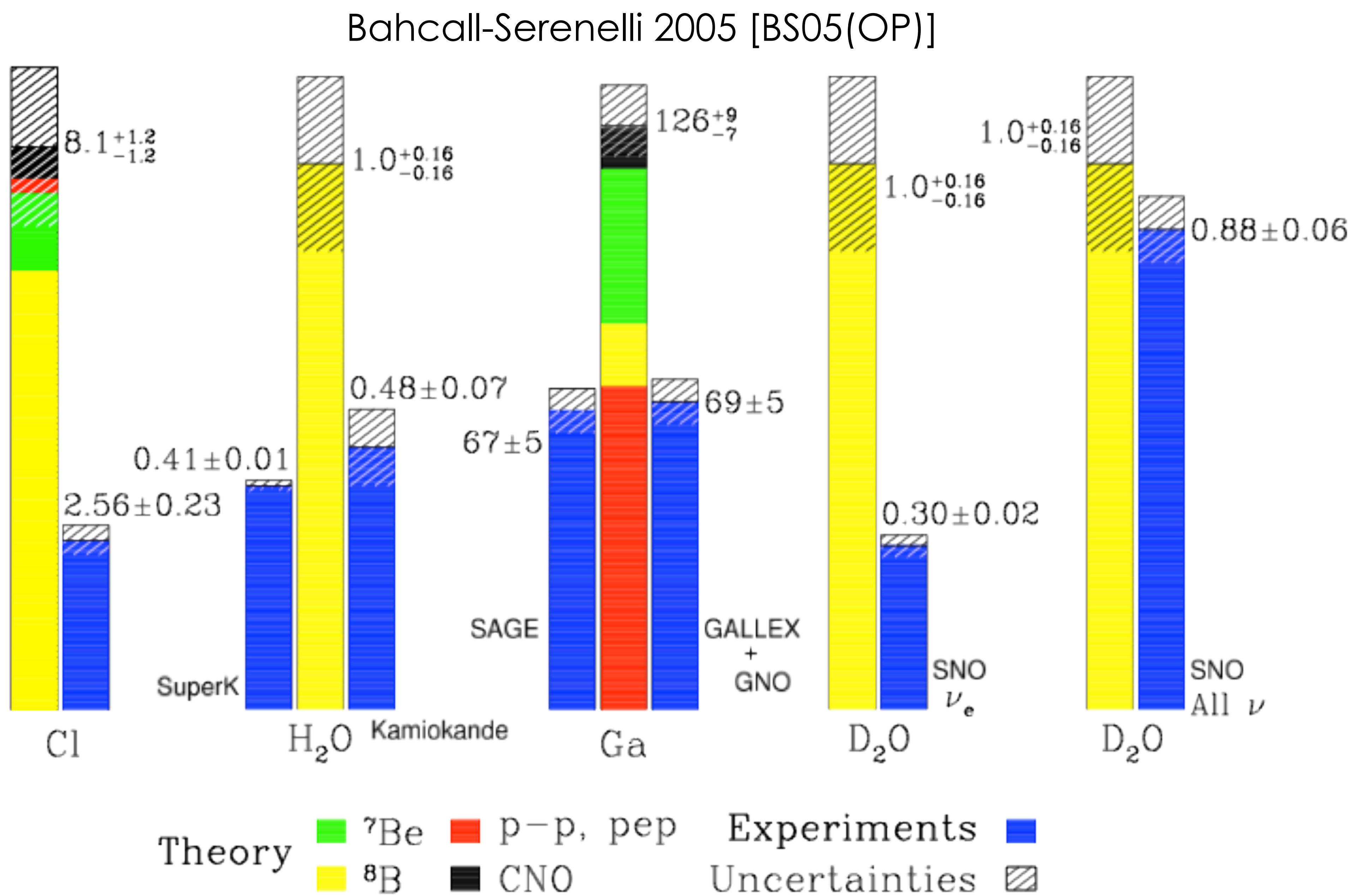
${}^{15}N + p \rightarrow {}^{12}C + \alpha$



The Solar Neutrinos



Solar Neutrino Oscillations



Matter Enhanced Neutrino Oscillations

- The electron neutrino survival probabilities measured by the different solar neutrino experiments are well described by "matter enhanced" oscillations

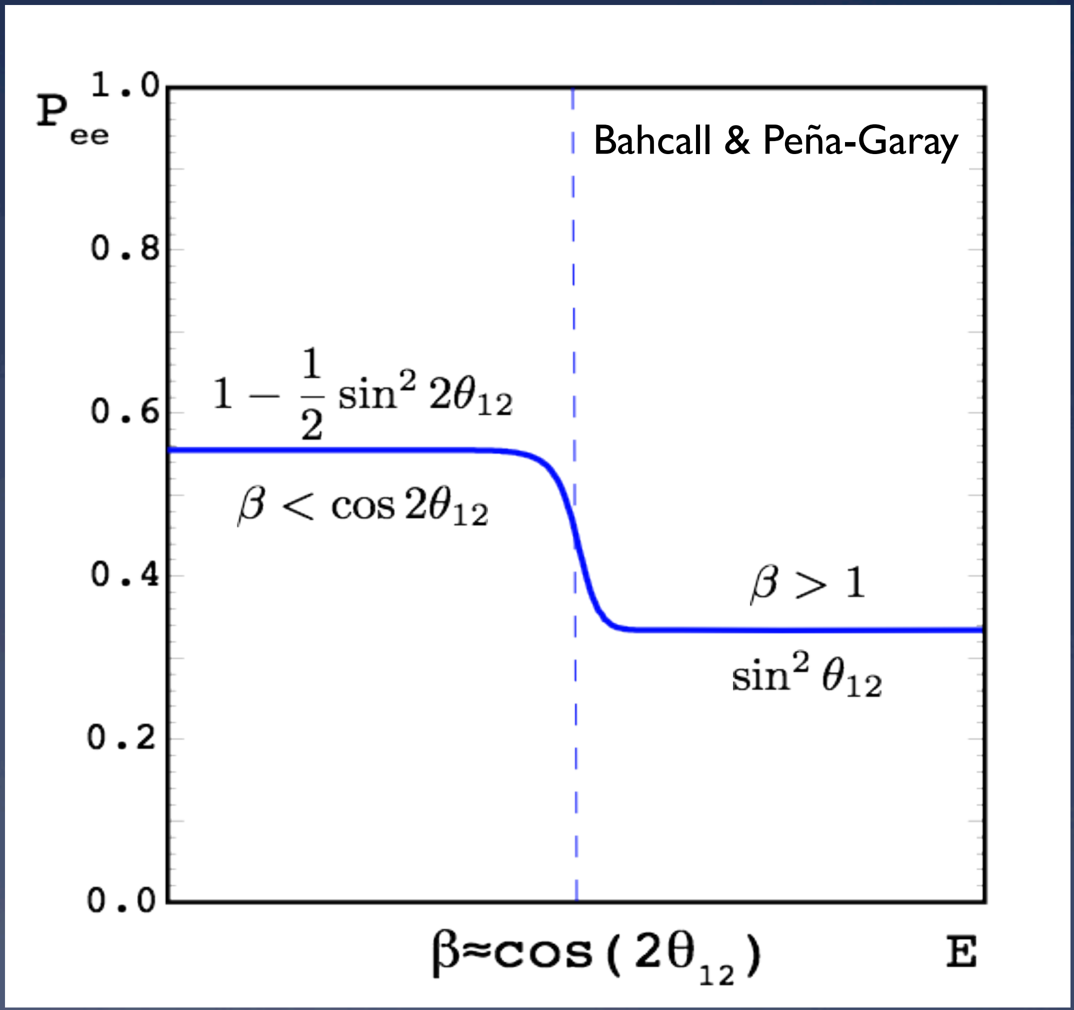
- Similar to quark oscillations (CKM matrix ➔ PMNS matrix), except that charged current interactions with matter add an additional effective mass term to ν_e flavour:

$$\begin{pmatrix} -\frac{\Delta m_{12}^2}{4E}\cos 2\theta_{12} + \sqrt{2}G_F N_e & \frac{\Delta m_{12}^2}{4E}\sin 2\theta_{12} \\ \frac{\Delta m_{12}^2}{4E}\sin 2\theta_{12} & \frac{\Delta m_{12}^2}{4E}\cos 2\theta_{12} \end{pmatrix}$$

- Note that because θ_{13} is small, solar neutrinos are well described by "two-flavour" oscillations

MSW Oscillation Regimes

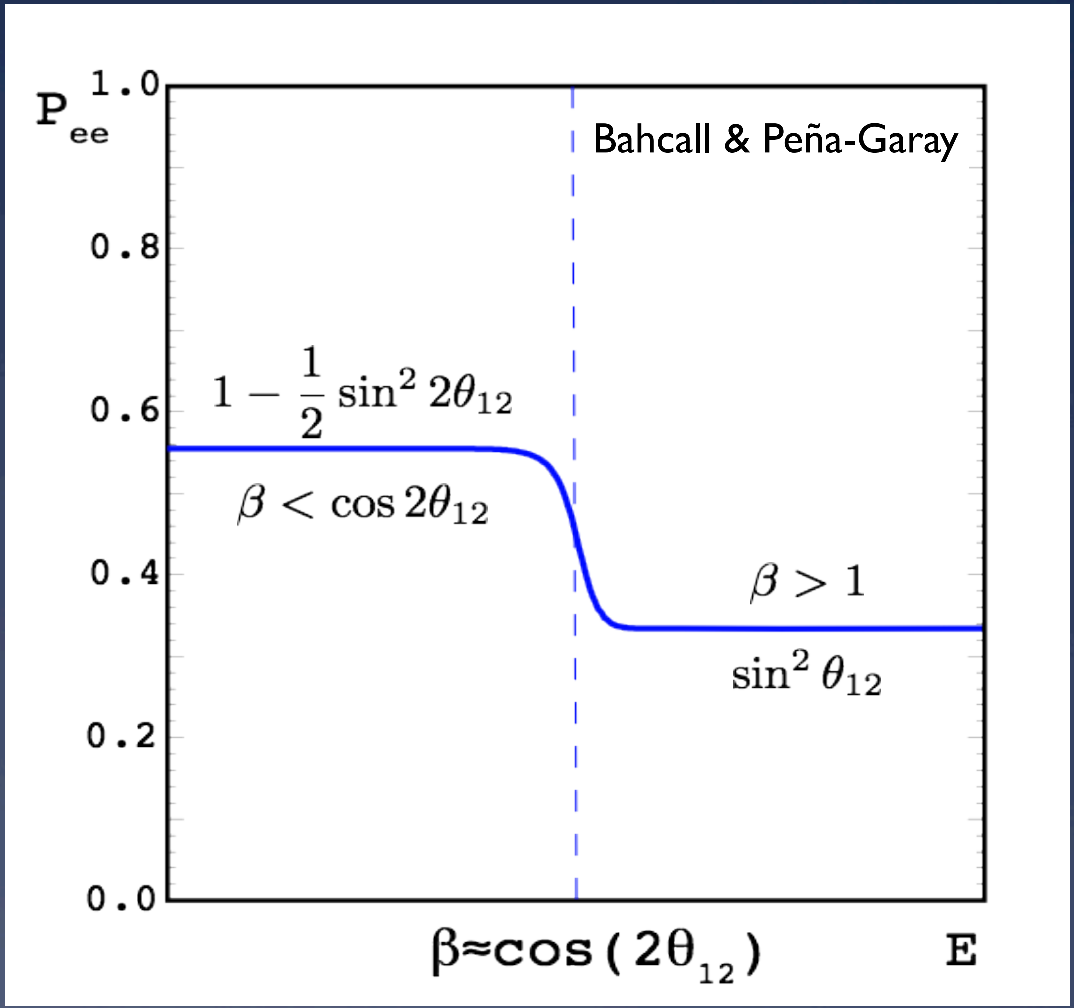
- At low energy (<~0.5 MeV) the effective mass term is small compared to the mass splitting
- Solar survival probability is just phase average of (quark-like) 'vacuum oscillations'



$$\beta = \frac{2^{3/2} G_F N_e E}{\Delta m^2}$$

MSW Oscillation Regimes

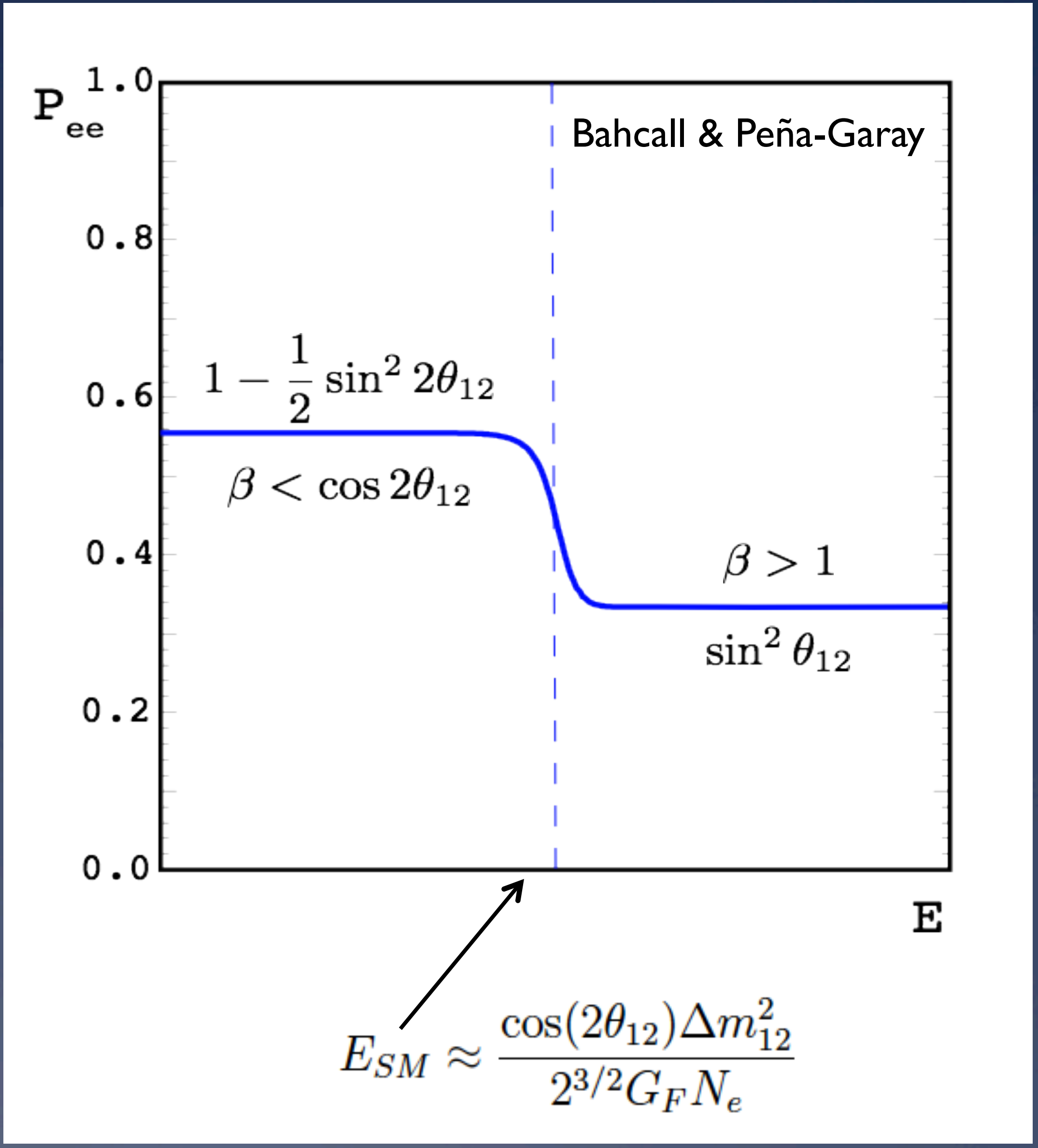
- At high energy (<~3 MeV) the effective mass term is large compared to the mass splitting
- The PNMS matrix changes, so that ν_e is more closely related to (heavier) ν_2's
- Adiabatic transition through solar density profile results in primarily ν_2 solar neutrino flux, giving large apparent mixing



$$\beta = \frac{2^{3/2} G_F N_e E}{\Delta m^2}$$

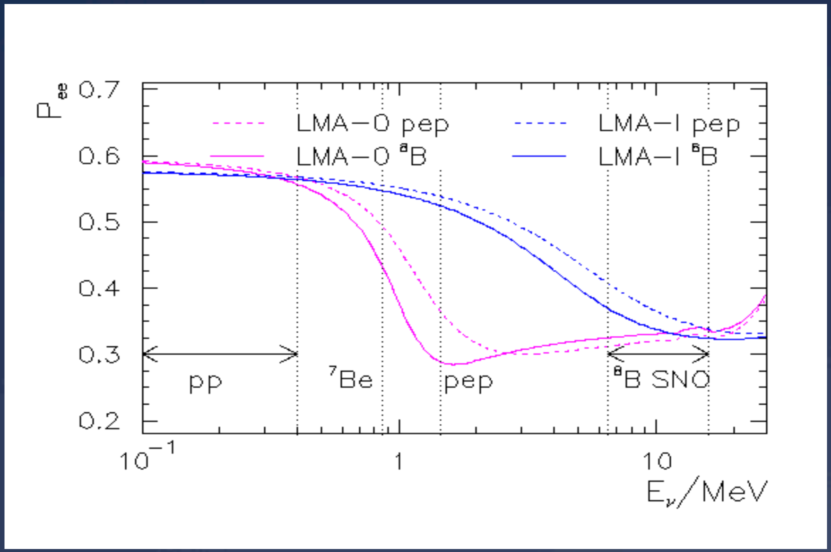
Study MSW Upturn

- To first order, vacuum and matter survival probabilities depend only on θ_{12}:
  - Not on the mechanism through which ν_e gains effective mass
  - Not on the mass splitting
- Transition region is sensitive to mass splitting, neutrino-matter coupling, and hence new physics

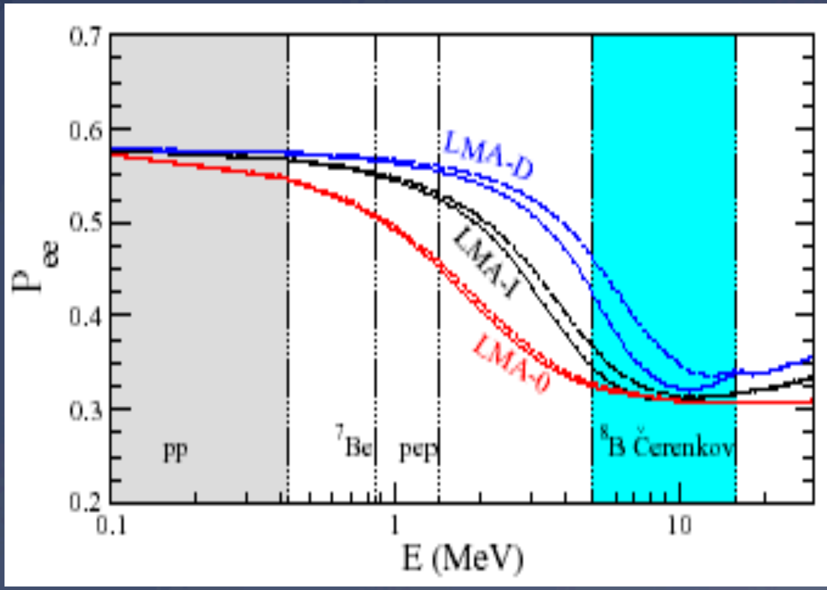


Possible Transition Region New Physics

Non-Standard Interactions

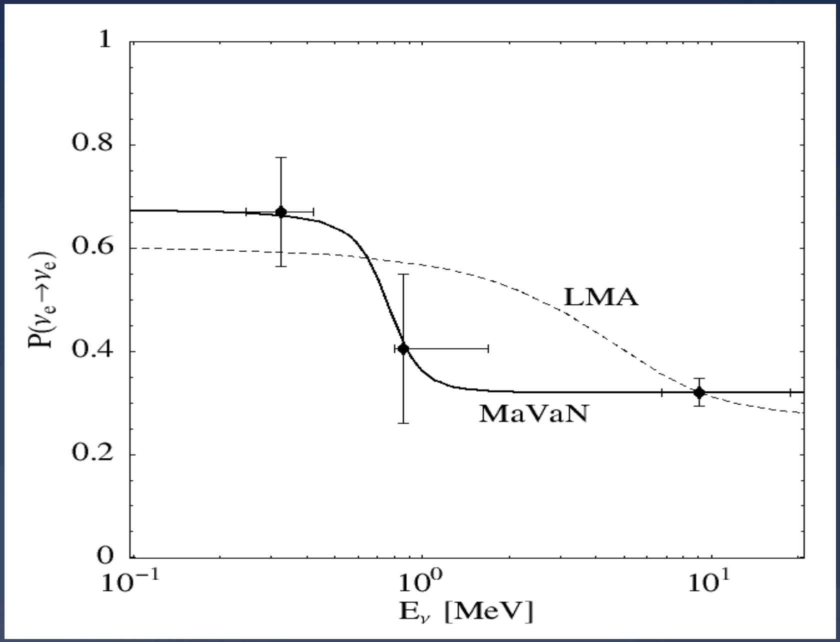


Friedland *et al.*, PLB 594 (2004)



Miranda *et.al.*, hep-ph/0406298 (2005)

Mass Varying Neutrinos

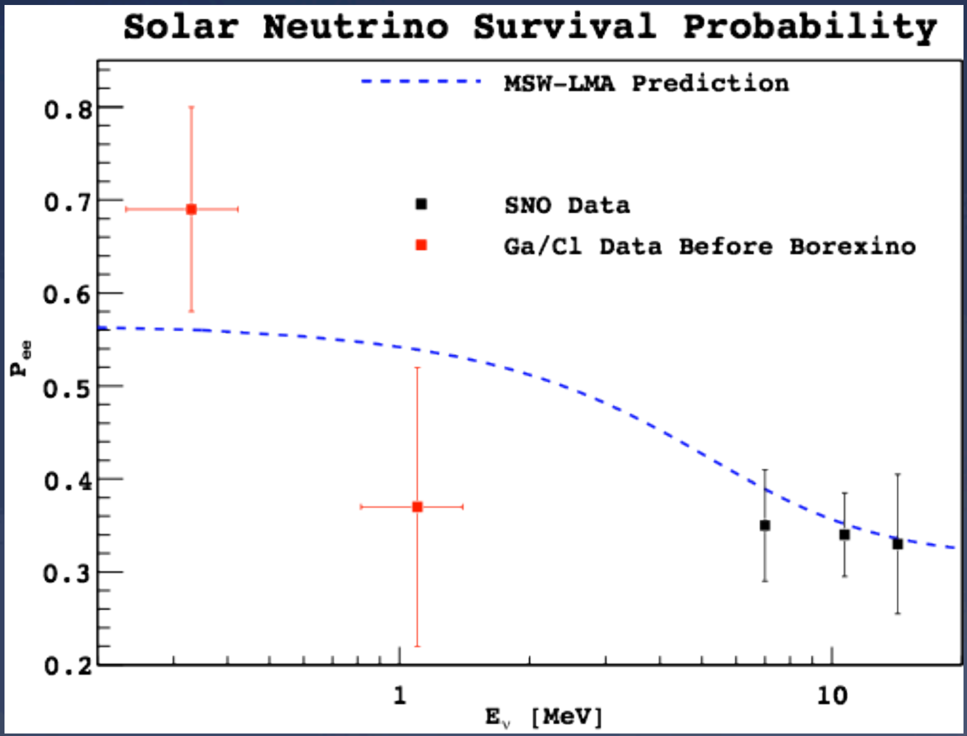


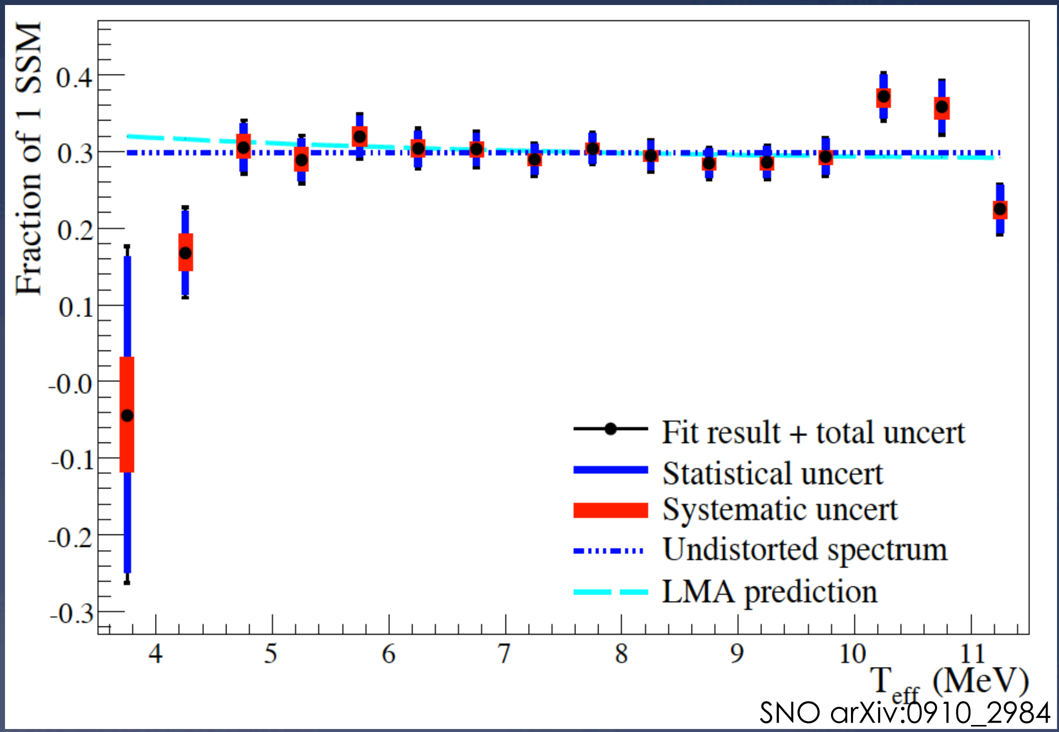
Barger *et al*. PRL 95 (2005)

Other Possibilities:

- CPT violations
- Large Θ_{13}
- Sterile neutrino admixture

(Solar) Experimental Constraints on Transition Region





Real-time measurements below 4MeV can confirm MSW and constrain new physics.

Solar Metallicity Controversy

- "Metallicity" (fraction of Z>2 elements) of the solar interior can be estimated in two ways:
  - Helioseismology vs. sound speed in solar models
  - Spectroscopic measurements of the photosphere, extrapolated via convection models
- "Old" spectroscopic metallicities (Grevesse and Sauval, Space Sci. Rev. **85**, 161 (1998)) in SSM gave good agreement with helioseismology
- "New" spectroscopic metallicities (Asplund, Grevesse and Sauval (Nucl. Phys. A **777**, 1 (2006)) are lower by ~1.4, no longer agree with helioseismology

Solar Metallicity Controversy

Bahcall, Serenelli and Basu, AstropJ 621, L85(2005)

Φ ($cm^{-2}s^{-1}$)	*pp* ($\times 10^{10}$)	^{7}Be ($\times 10^{9}$)	^{8}B ($\times 10^{6}$)	^{13}N ($\times 10^{8}$)	^{15}O ($\times 10^{8}$)	^{17}F ($\times 10^{6}$)
BS05 GS 98	5.99	4.84	5.69	3.07	2.33	5.84
BS05 AGS 05	6.05	4.34	4.51	2.01	1.45	3.25
Δ	+1%	-10%	-21%	-35%	-38%	-44%
σ SSM	±1%	±5%	±16%	±15%	±15%	±15%

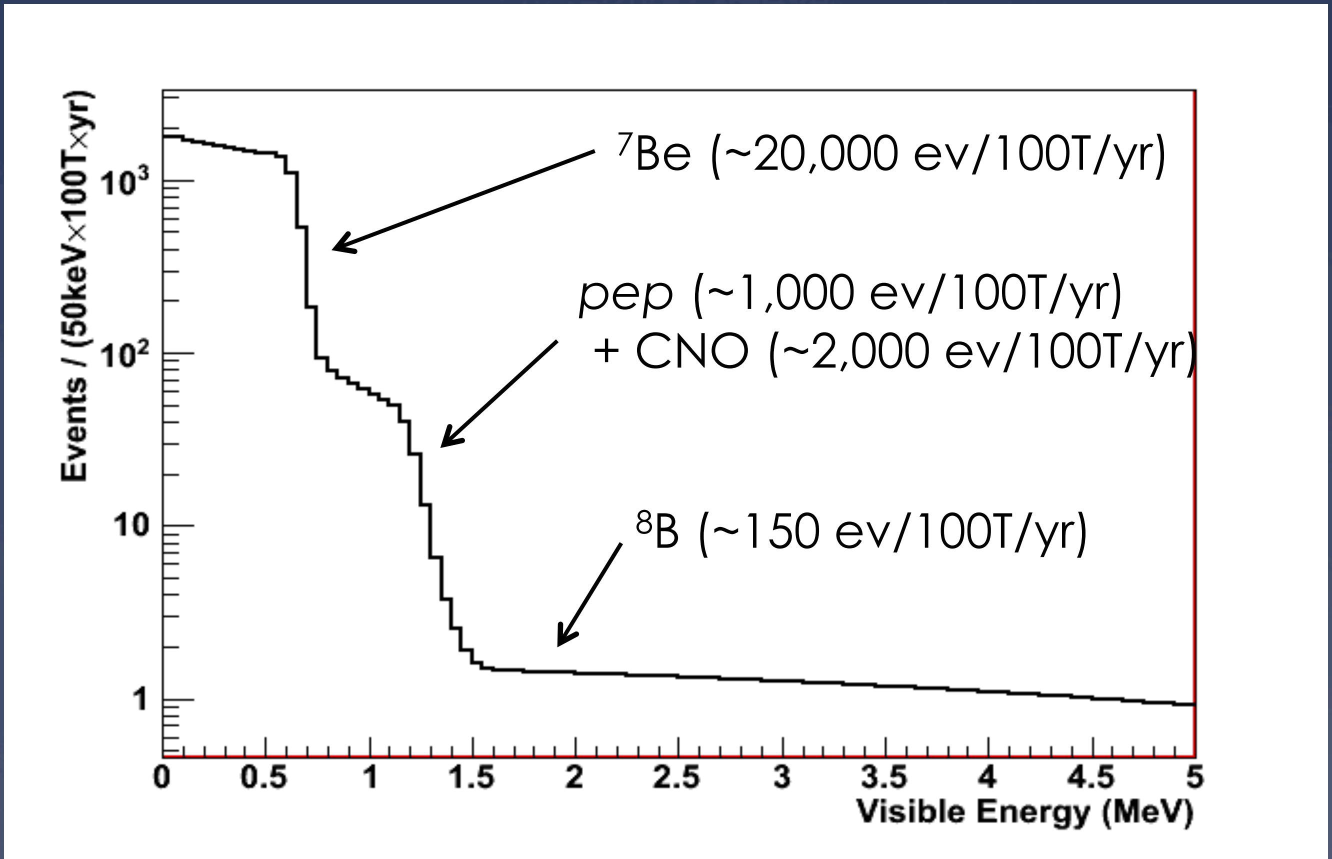
Neutrino flux measurements can constrain solar metallicity!

Neutrino Detection With Liquid Scintillator

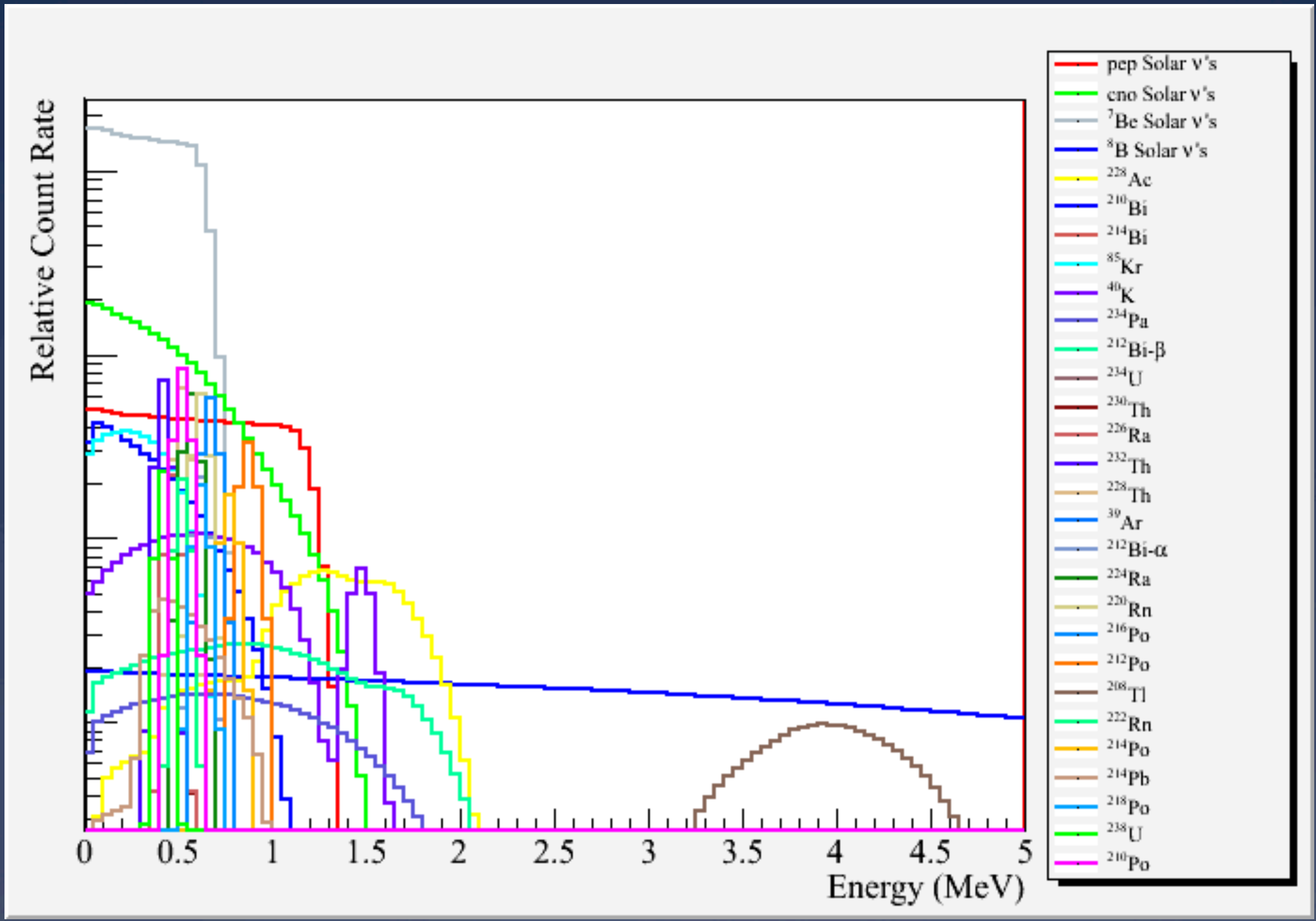
- Neutrinos interact via neutrino-electron elastic scattering
- Detect scintillation light from recoiling electron
  - Good position reconstruction (10-15cm) from time-of-flight
  - Low energy threshold (~60keV)
  - Good energy resolution (~500p.e./MeV)
- Calorimetric measurements only, no directional sensitivity
  - Can't distinguish neutrino events from β / γ backgrounds

Neutrino Signal in Liquid Scintillator

- Kinematic relationship between the neutrino energy and the electron recoil



Backgrounds in a Liquid Scintillator



Energy range of interest is within the reach of natural radioactivity, and event-by-event background rejection in scintillator is difficult or impossible….

Classes of Background

- Internal cosmogenics
  - Short-lived radioactivity induced by muons
- External backgrounds
  - Gamma-rays and neutrons from the rock
- Internal radiogenics
  - Radioactive isotopes in detector materials

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Deep site, veto

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Deep site, veto

Shielding, layered design

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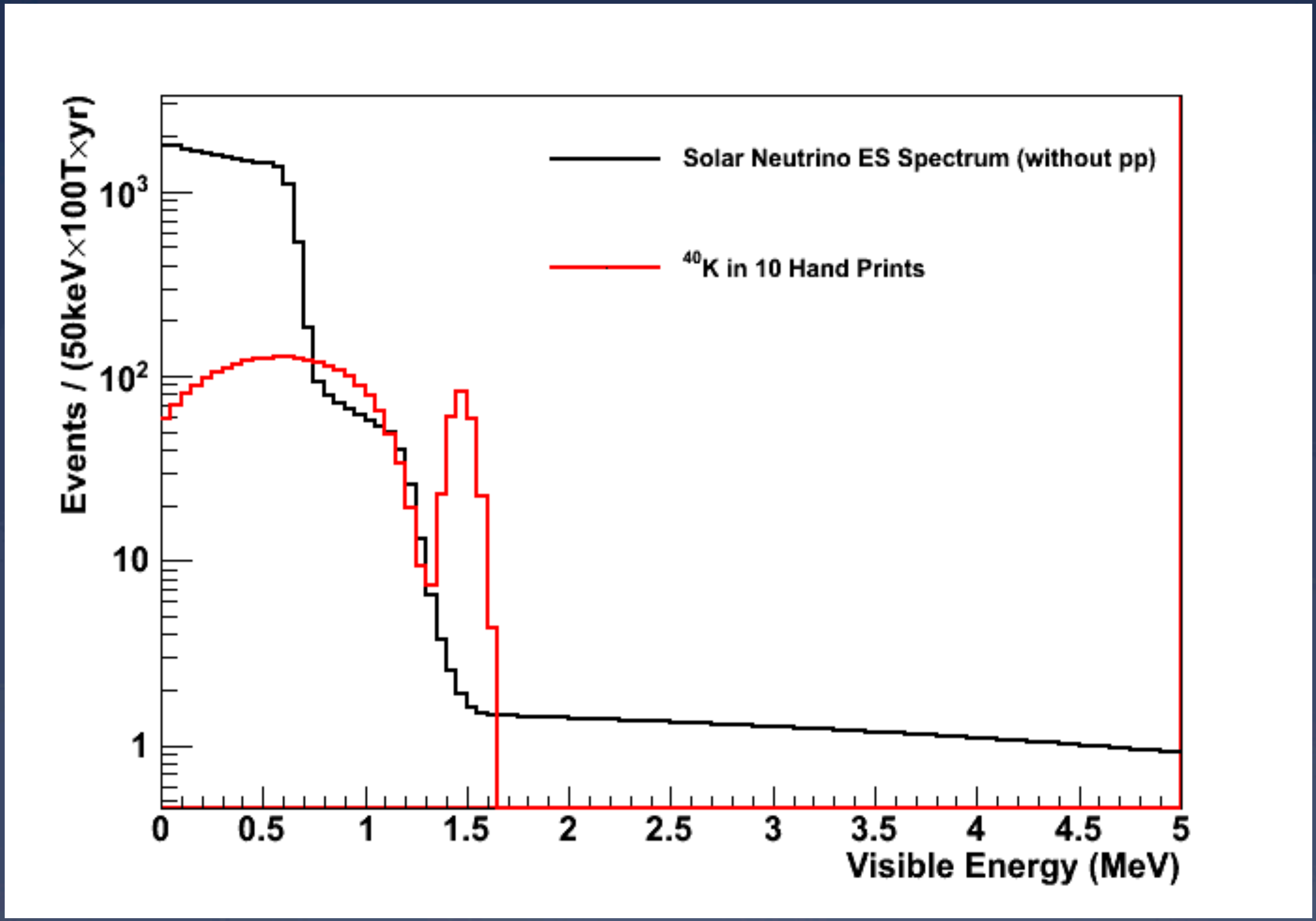
Deep site, veto

Shielding, layered design

CLEAN, CLEAN, CLEAN!

Backgrounds in a Liquid Scintillator

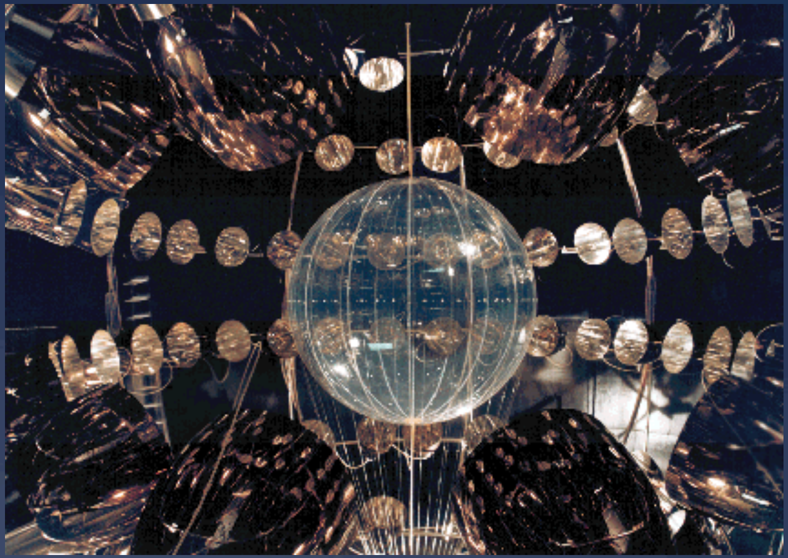


…and signal rates are low.

Suppressing backgrounds from natural radioactivity is key to studying solar neutrinos.

Internal Radiogenic Requirements

Contaminant	Typical Concentration	Borexino Requirement
^{14}C	10^{-12}g/g	10^{-18}g/g
^{85}Kr	1 Bq/m^3	<2x10^{-7} Bq/m^3
^{238}U	10^{-4}g/g	10^{-16}g/g
^{232}Th	10^{-4}g/g	<10^{-16}g/g



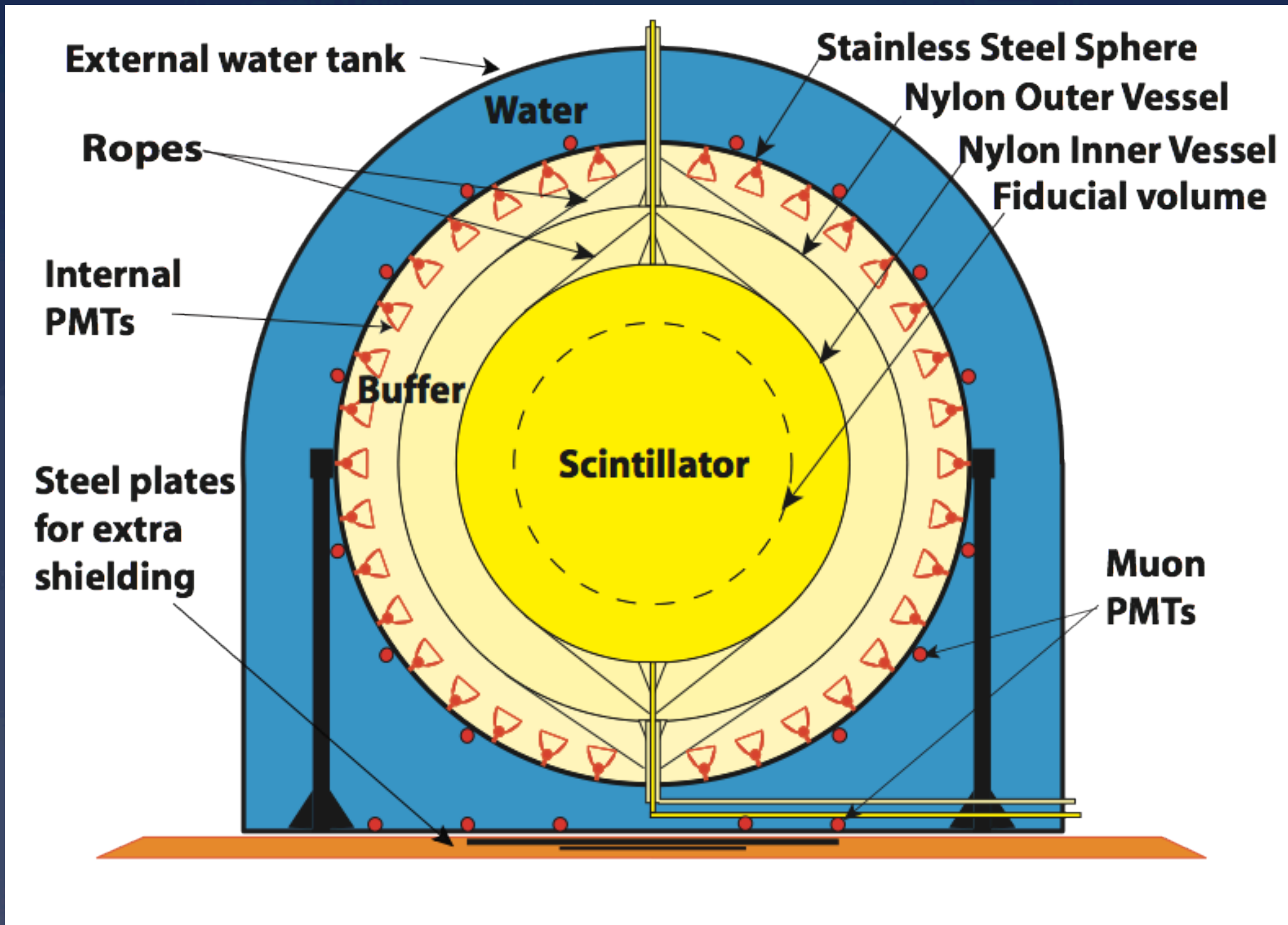
- At the time that Borexino was conceived it was not clear that these purity levels were achievable
- Long program of materials screening and development of purification and clean handling techniques
- Feasibility of overall radiopurity demonstrated with a series of "counting test facilities"

Borexino Backgrounds

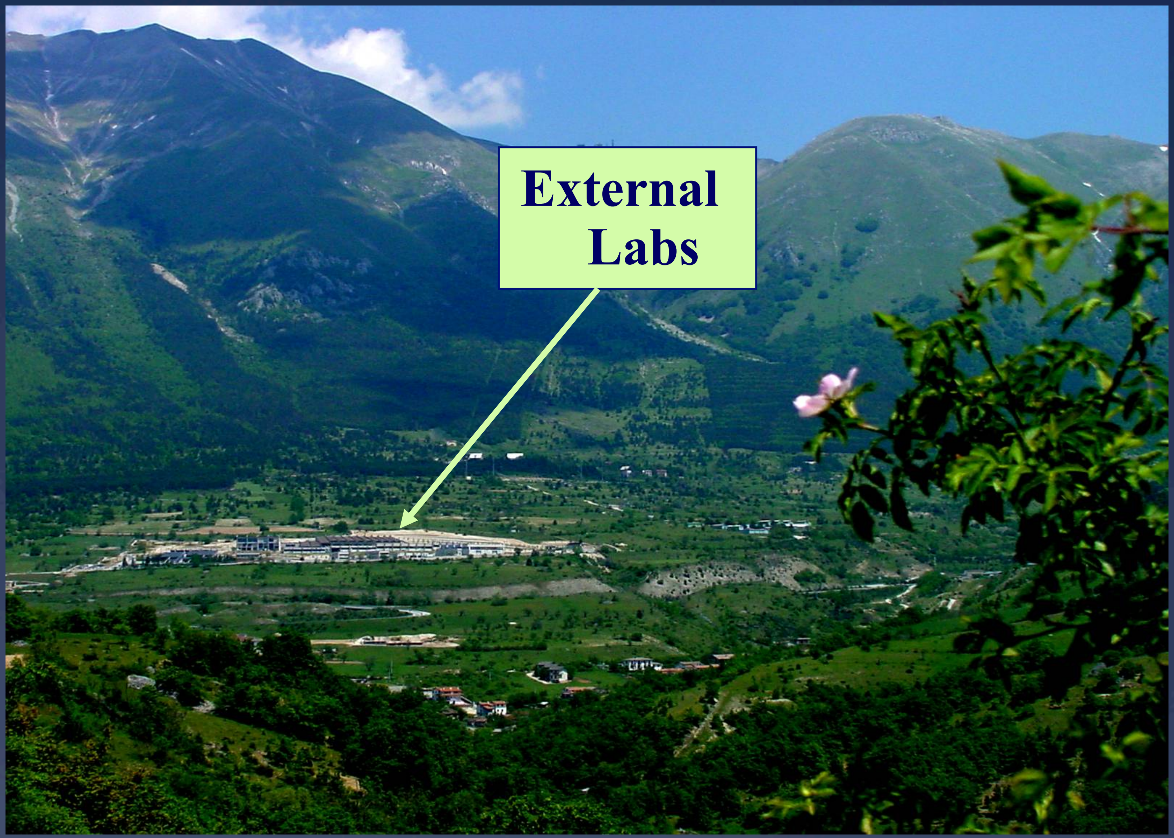
- Borexino achieved unprecedented levels of purity and cleanliness
  - Still working to push even lower!
- Enabled not only the Borexino measurements, but established techniques for a generation of neutrino and dark matter experiments

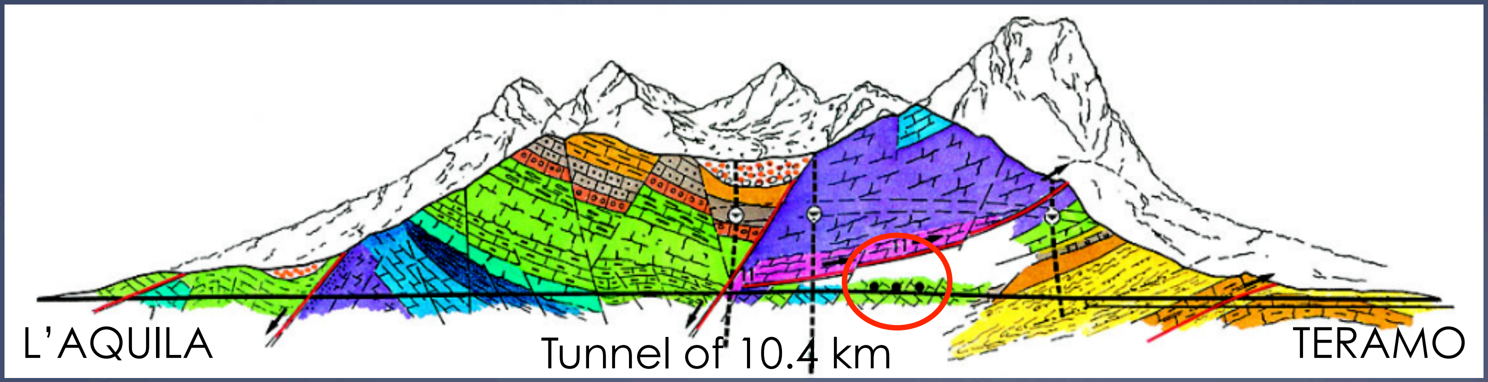
Contaminant	Source	Normal Conc.	Borex Req.	Reduction Method	Borex Achieved
μ	Cosmic	$200/(s \cdot m^2)$	$10^{-10} / (s \cdot m^2)$	Underground, active veto	$<10^{-10}/(s \cdot m^2)$
^{14}C	Scintillator	10^{-12} g/g	10^{-18} g/g	Old oil	10^{-18}g/g
^{238}U	Dust	10^{-4} g/g	10^{-16} g/g	Purification	$<10^{-17}$g/g
^{232}Th	Dust	10^{-4}g/g	$<10^{-16}$ g/g	Purification	$<10^{-17}$g/g
^{85}Kr	Air	1 Bq/m^3	<0.01ppt	LAKN	<0.035 ppt
^{11}C	Cosmogenic	25 /day/100ton	~10/day	μ+n coincidence	3/day/100ton

The Borexino Detector

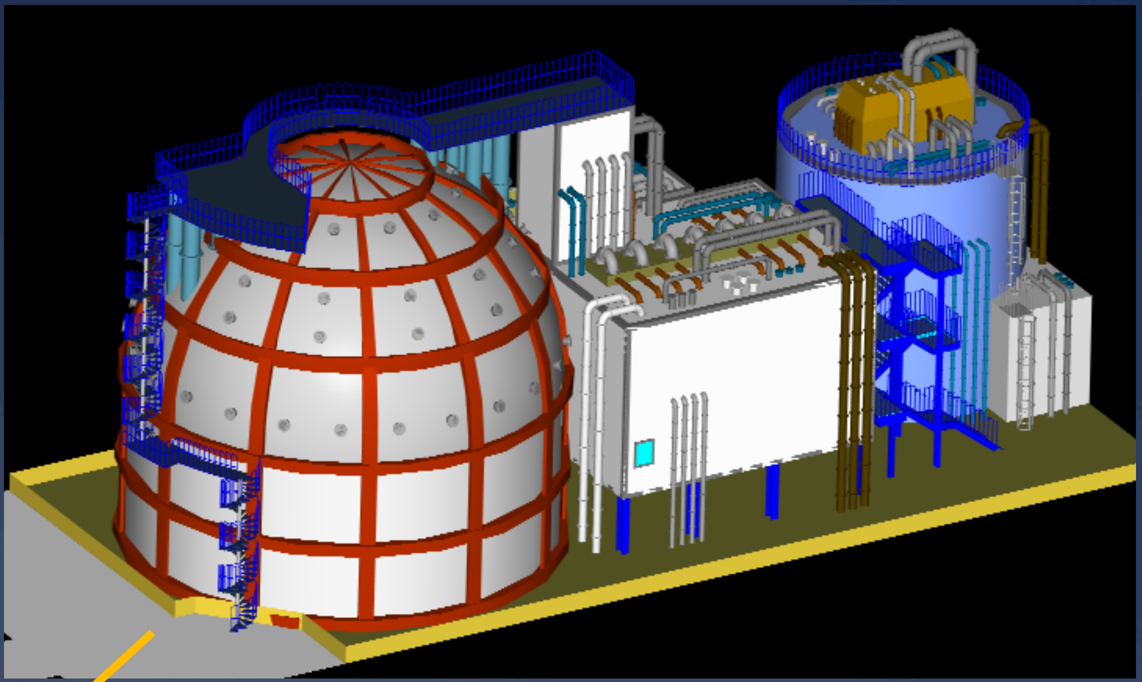


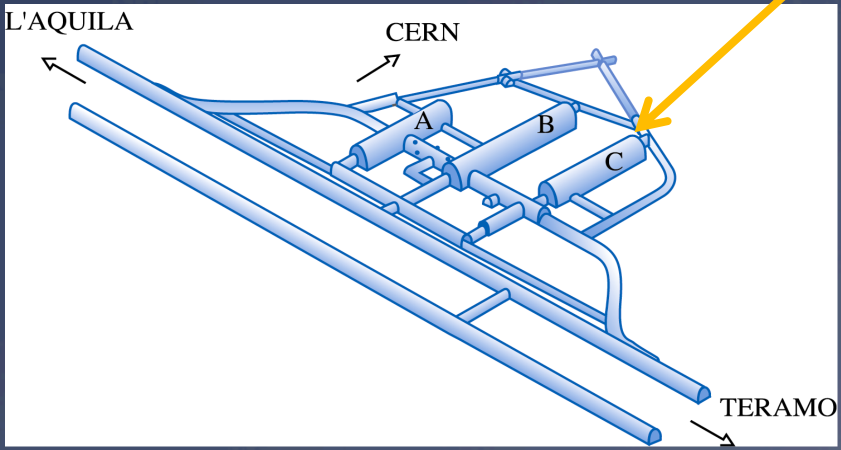
Laboratori Nazionali del Gran Sasso





Borexino at LNGS





~4600' overburden reduces cosmic ray flux to ~$3 \times 10^{-8} cm^{-2} s^{-1}$ (~10^{6} lower than on surface)

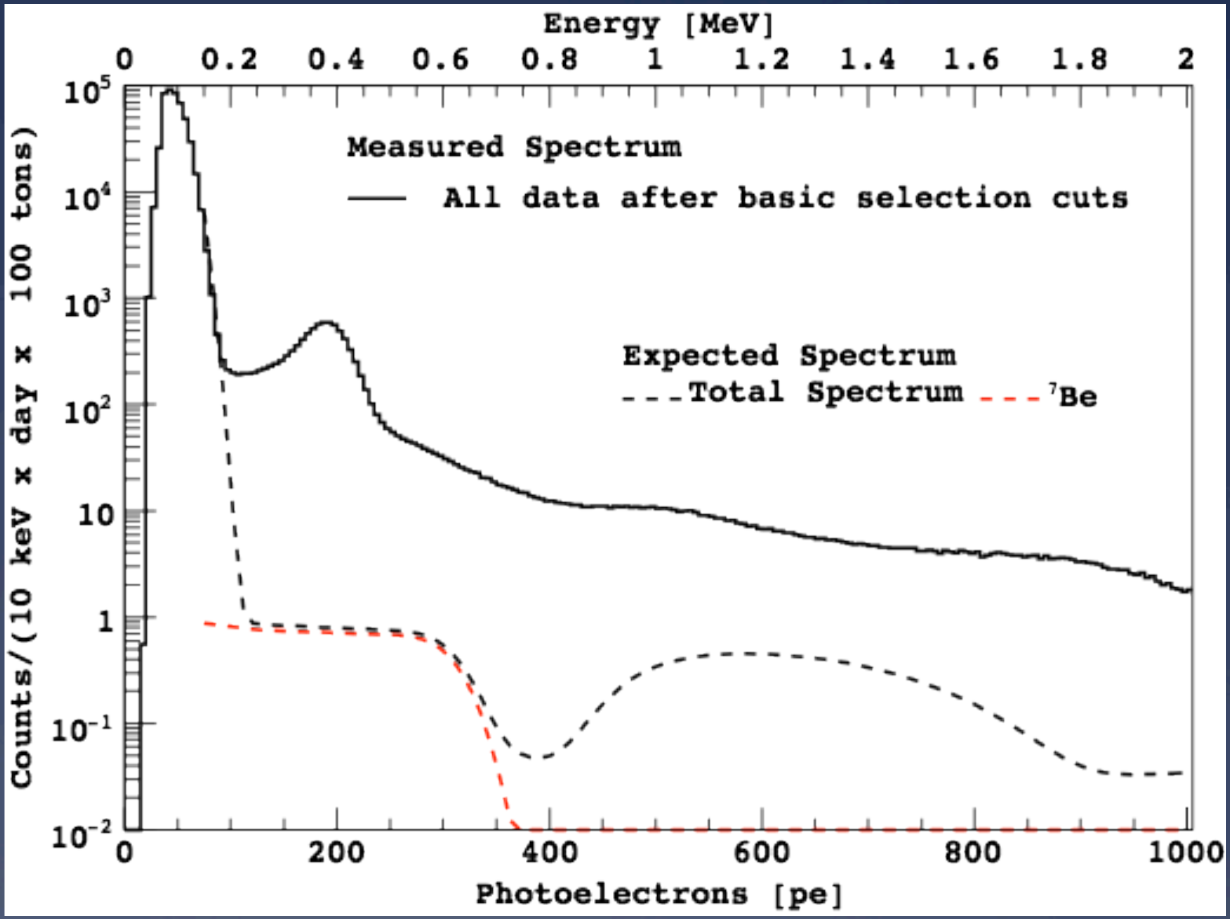
Borexino Physics Results

- ^{7}Be Solar Neutrinos
- ^{8}B Solar Neutrinos
- Geo-neutrinos

Borexino Low Energy (^{7}Be) Analysis

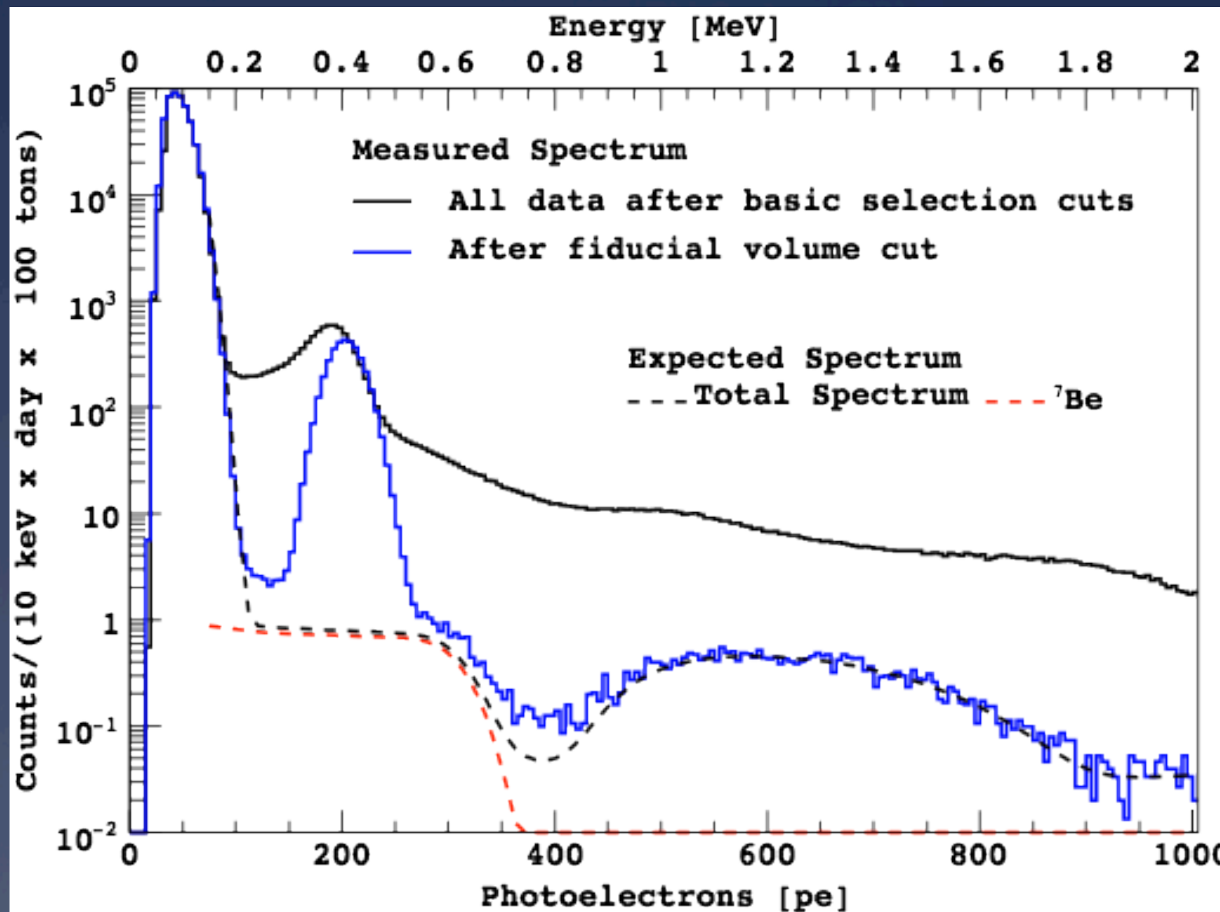
(PRL 101 9 (2008))

- Basic event selection:
  - Veto muons + 2ms for neutrons and fast cosmogenics
  - Reject events within 3hrs and 85cm of ^{214}Bi-^{214}Po co-incidences to reduce internal radon daughters



Borexino Low Energy (^7Be) Analysis

- Cut residual external gammas and backgrounds from the nylon vessel by applying a fiducial volume cut
  - r < 3m
  - |z| < 1.8m to reduce backgrounds from the "poles"



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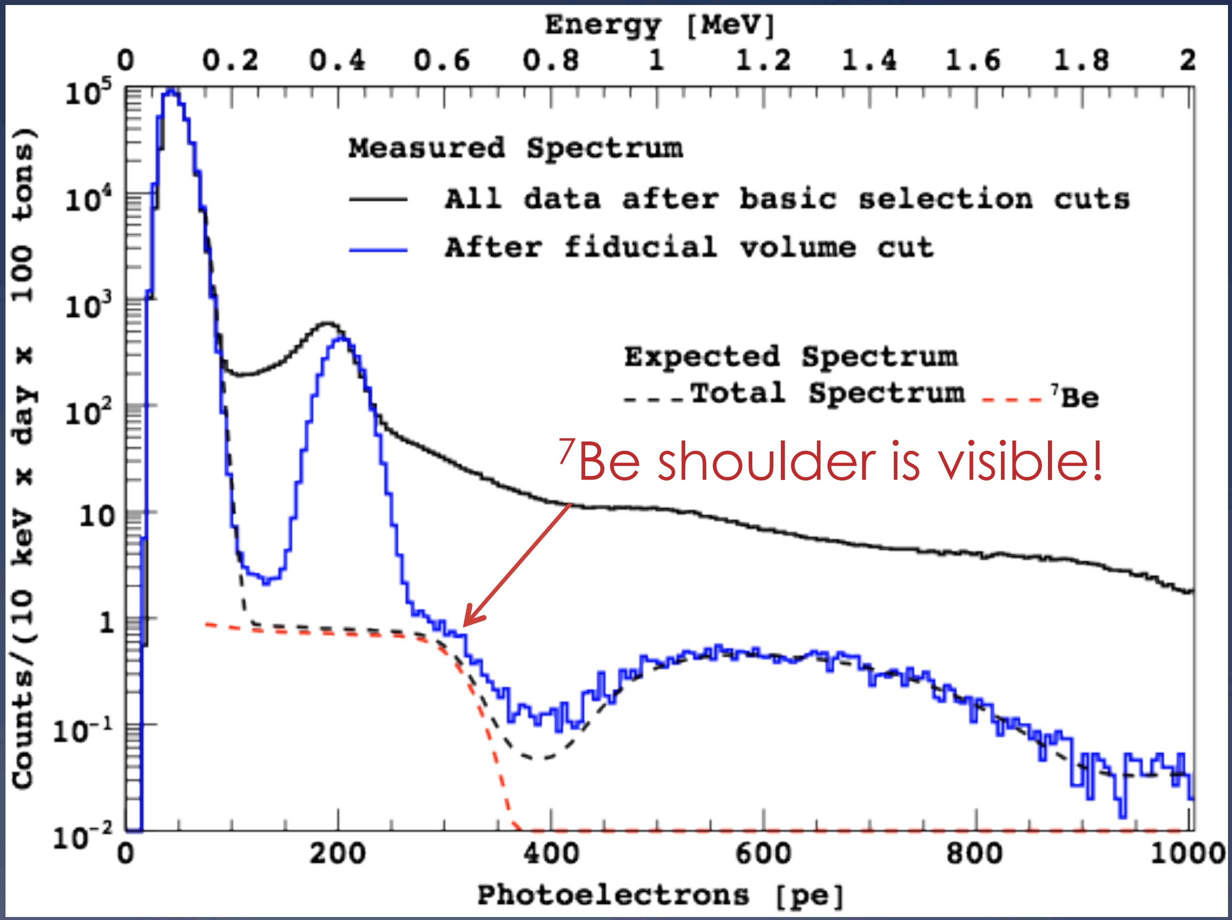

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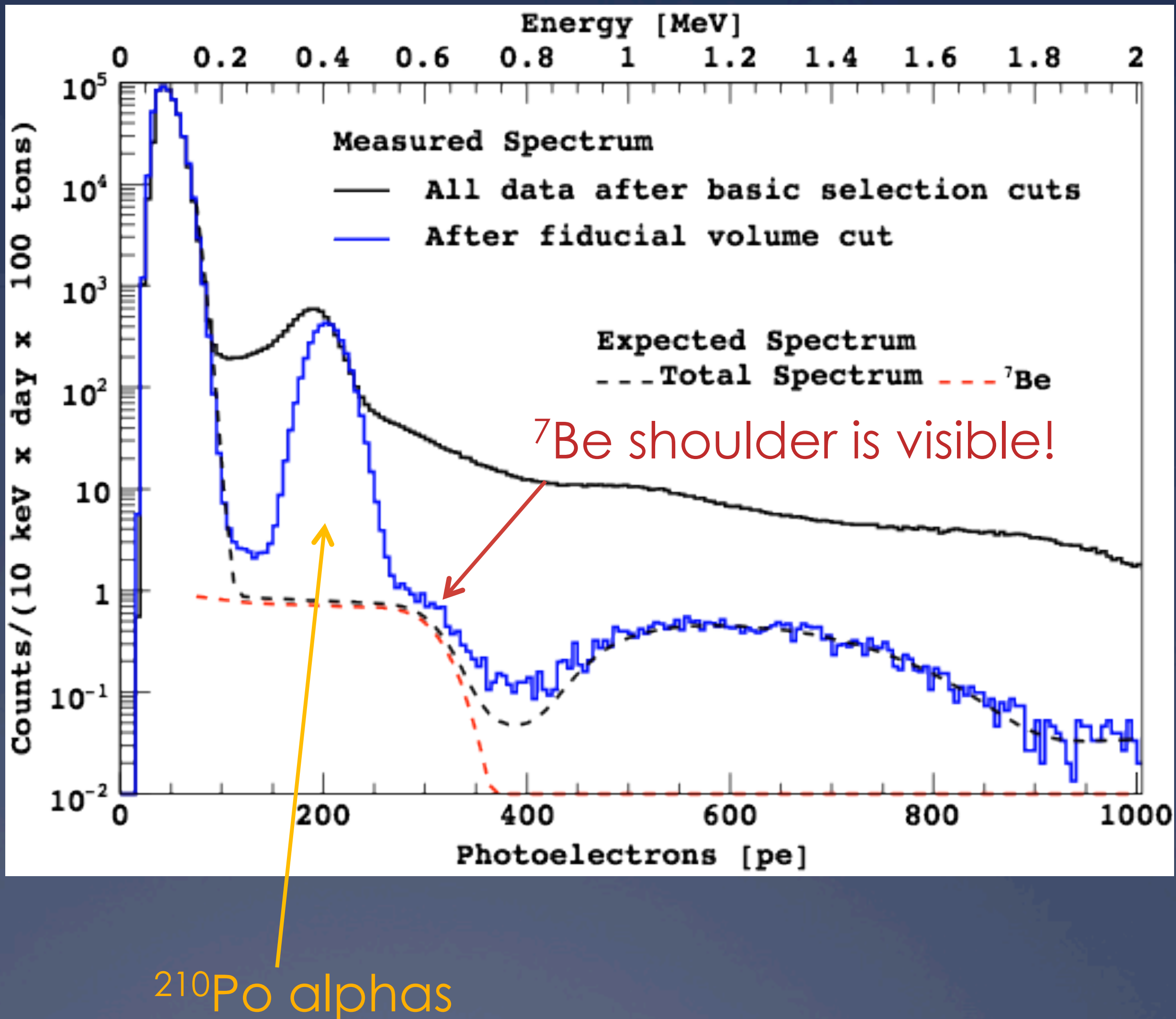
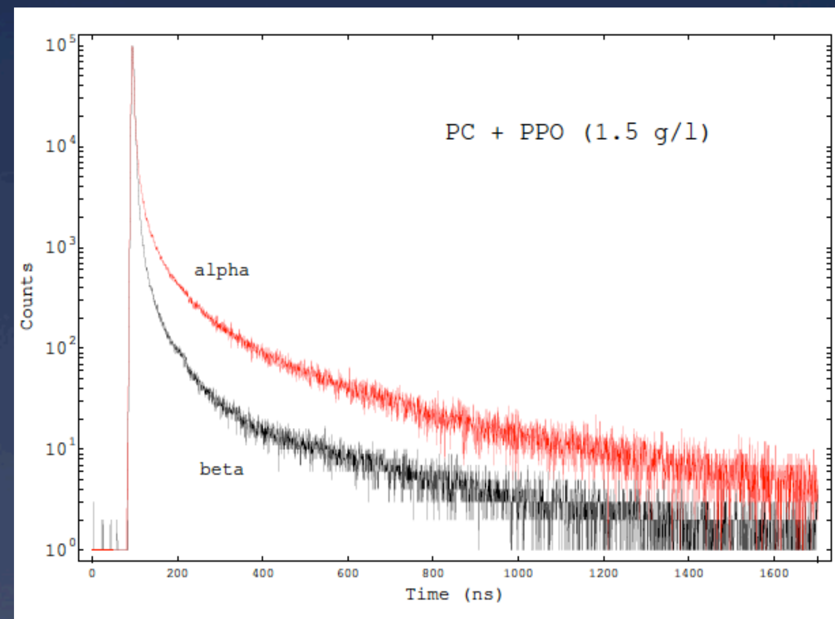
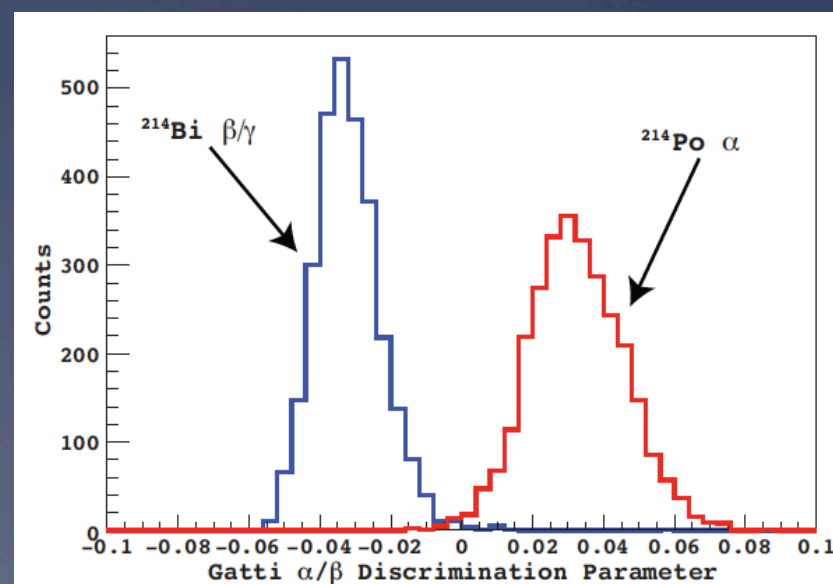


α - β Separation by PSA

- In organic scintillator, particles with higher ionization density produce more “slow” light
- Separation based on “Gatti Parameter”
  - Weight signal, S, in time bin i by difference ratio of average α and β pulse shapes in bin i



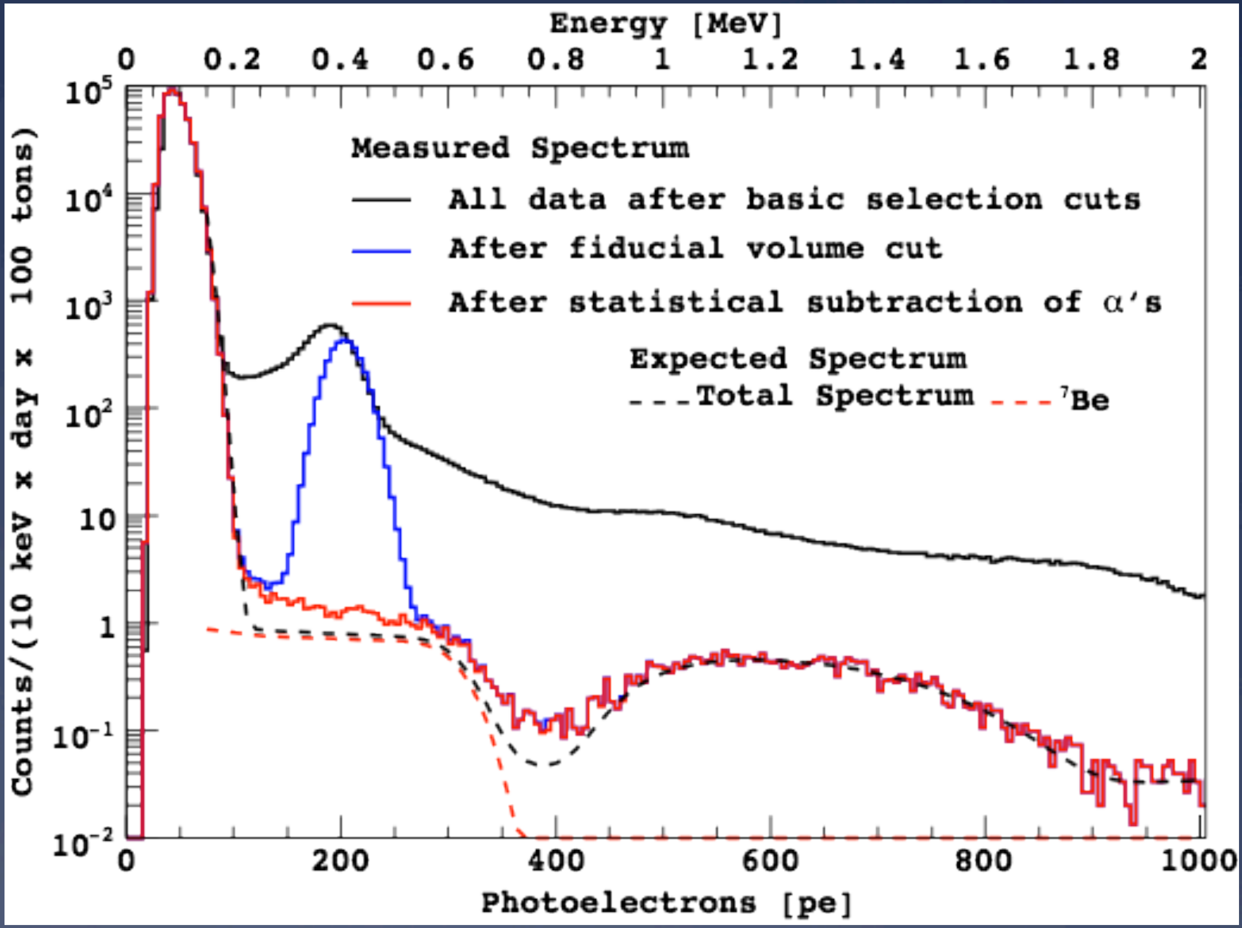


$$G = \sum_i P_i S_i$$

$$P_i = \frac{(\overline{\alpha_i} - \overline{\beta_i})}{(\overline{\alpha_i} + \overline{\beta_i})}$$

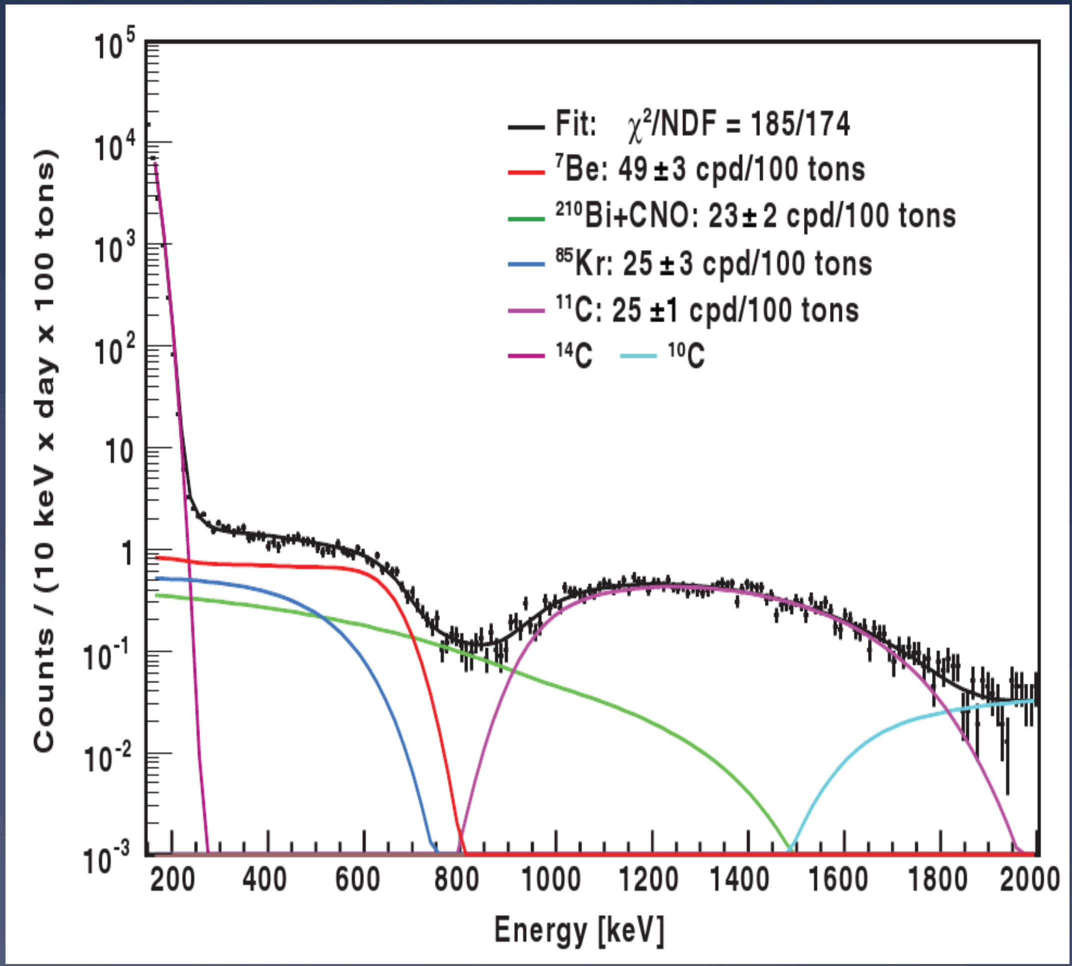
‘Statistical Selection’ by PSA

- Determine the number of electron-like events bin-by-bin using the Gatti distribution
- All that remains is signal and small residual backgrounds:
  - Long-lived cosmogenics (^{11}Be, ^{11}C, ^{10}C, etc)
  - Unvetoed radiogenics (^{210}Bi, ^{85}Kr, ^{208}Tl, etc)



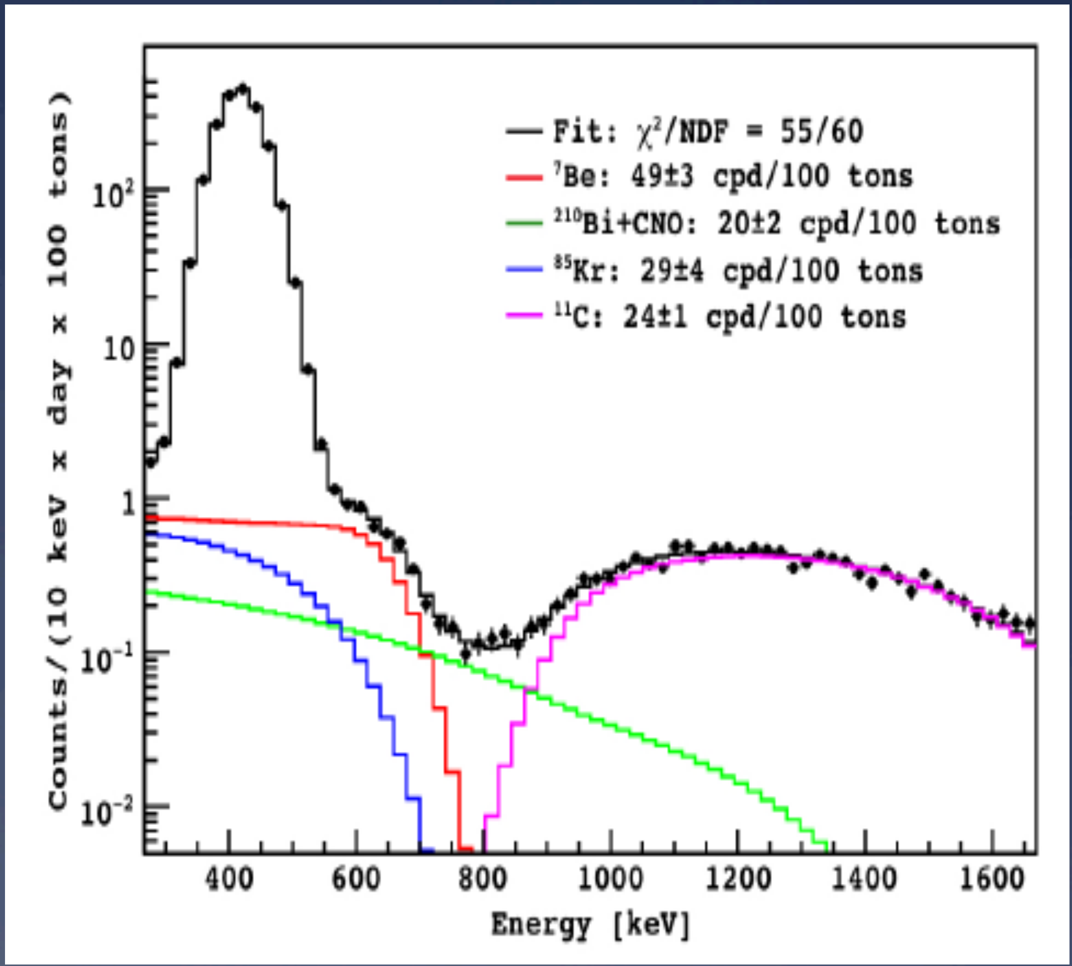
Borexino ^{7}Be Signal Extraction

- Likelihood fit to the energy spectrum
- Combine ^{210}Bi + CNO due to similar spectra
- Fix pep, pp fluxes to SSM
- Include residual ^{210}Po



Borexino ^{7}Be Signal Extraction

- Consistent results without using alpha rejection



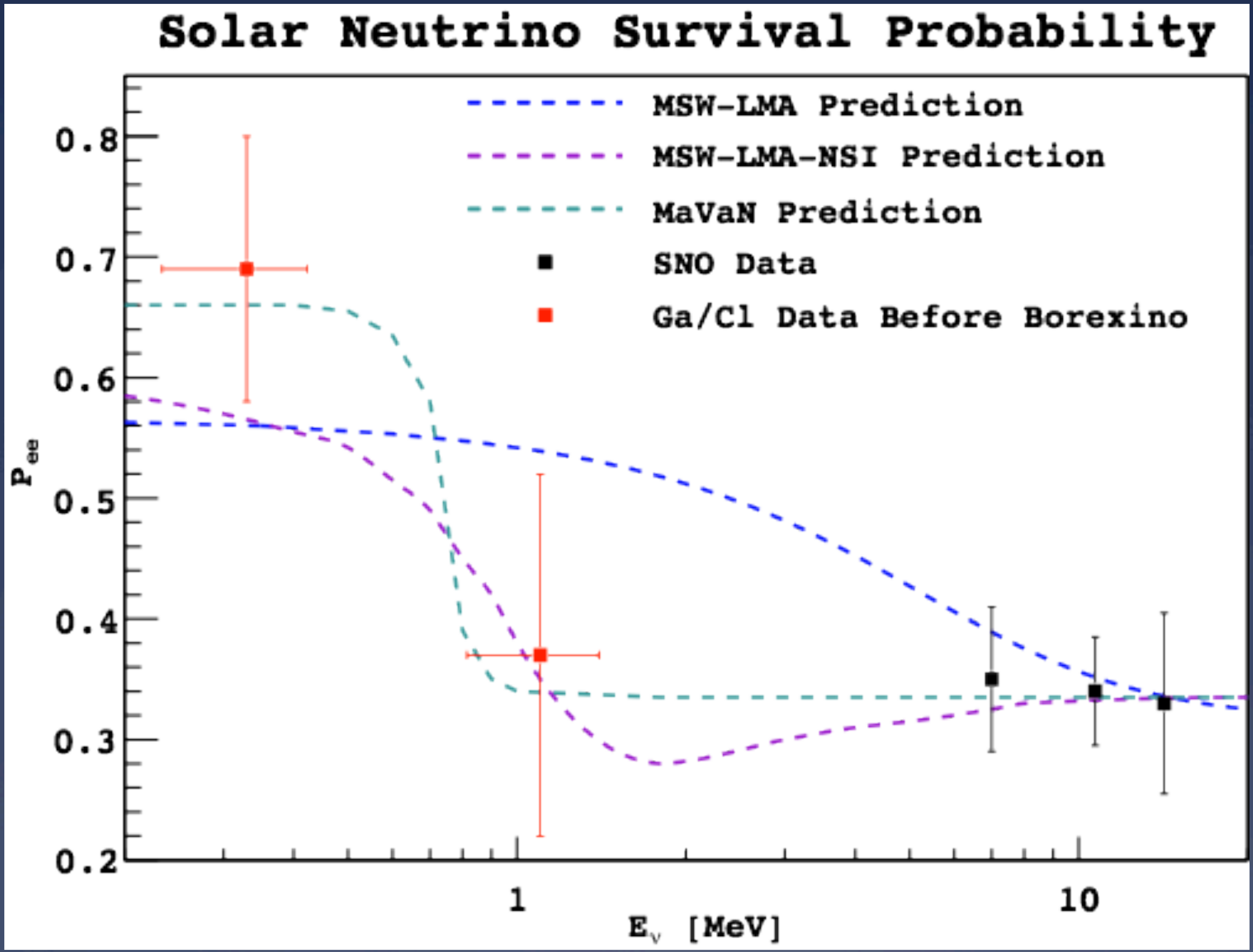
Borexino ^{7}Be Flux Result

- Based on first 192 live-days
- Before internal calibrations, so dominant systematics were fiducial volume (6%) and detector response (6%)

Total Scintillator Mass	0.2	Fiducial Mass Ratio	6.0
Live Time	0.1	Detector Resp. Function	6.0
Efficiency of Cuts	0.3		
Total Systematic Error			8.5

Borexino ^{7}Be counting rate: $49 \pm 3_{stat} \pm 4_{sys}$ /(d 100T)

Results on MSW Upturn



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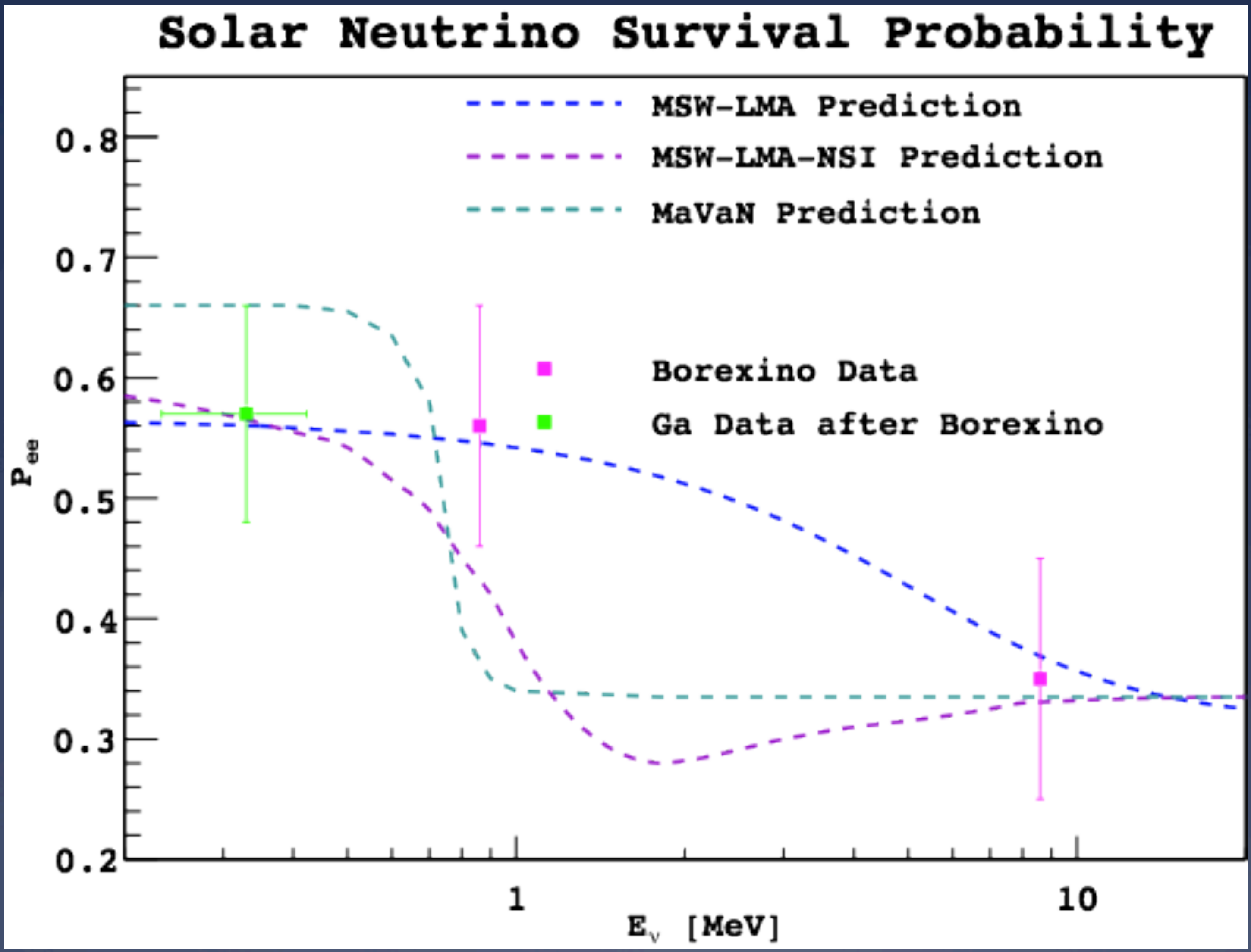

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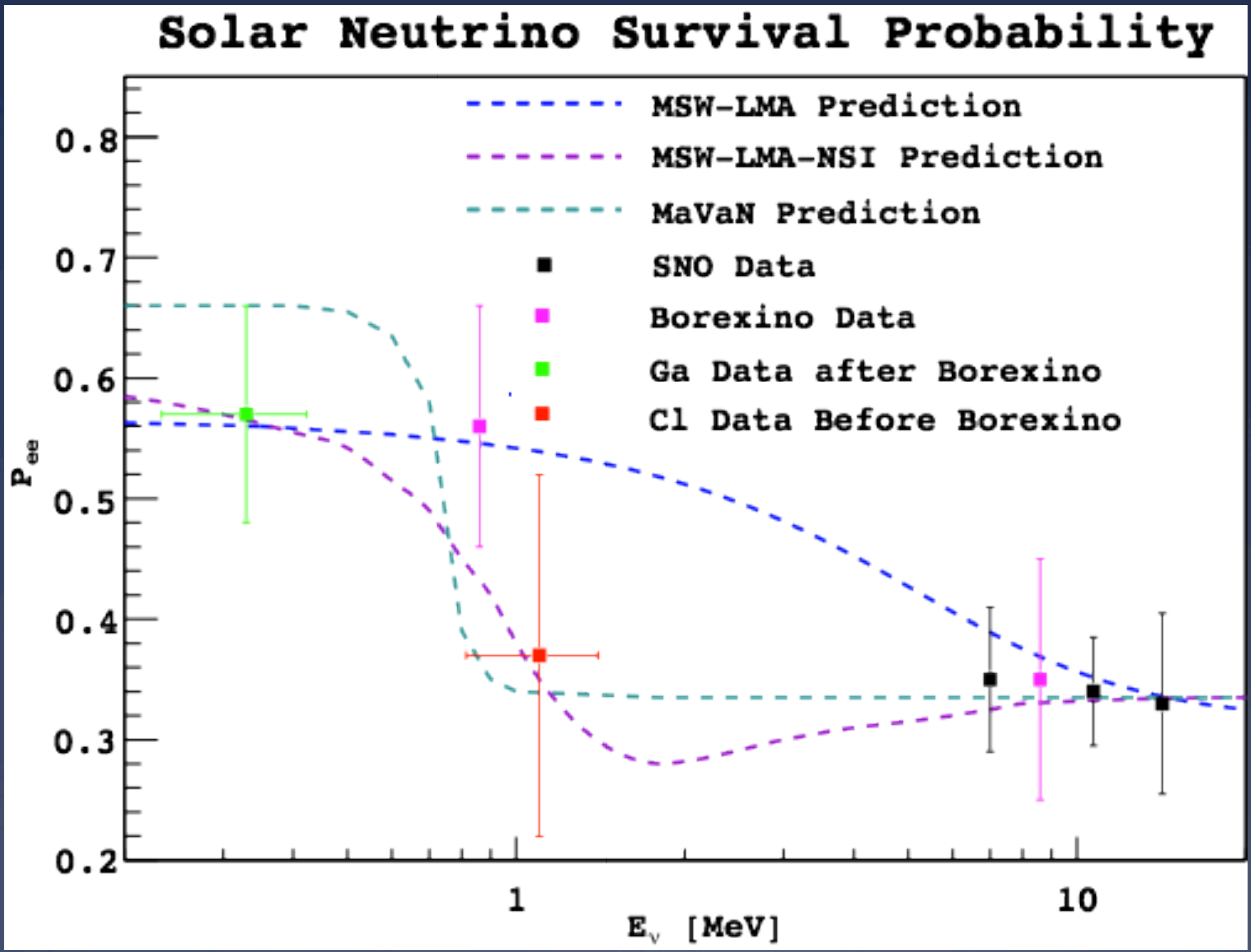


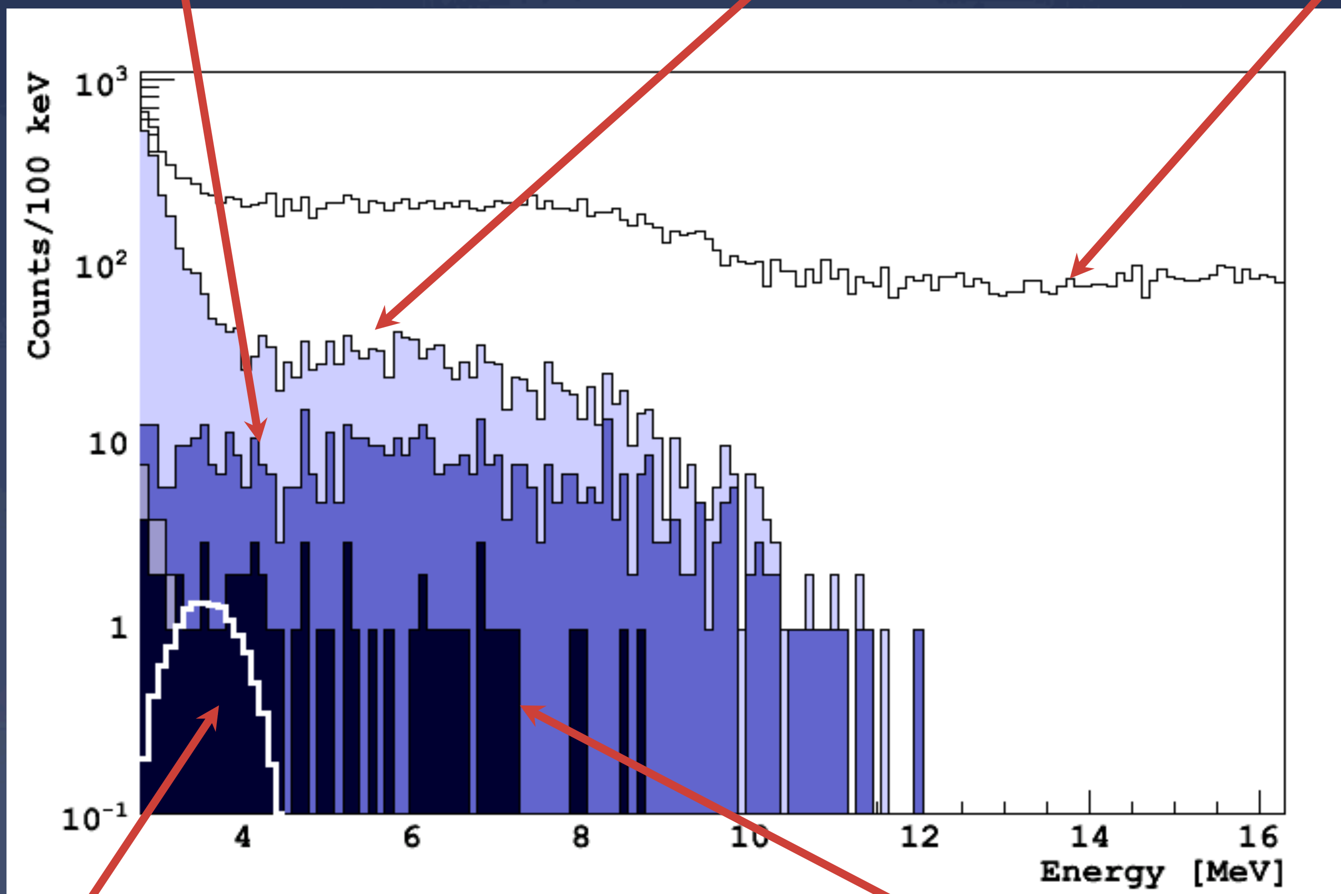
Borexino High Energy Analysis (^{8}B)

(arXiv:0808.2868, submitted to PRD)

After Fiducial Cut

After Muon Cut

All Data



^{208}Tl Contamination

After removing ^{214}Bi and Cosmogenics

Borexino ^{8}B Analysis

Cut	Counts 3.0–16.3 MeV	Counts 5.0–16.3 MeV
All counts	1932181	1824858
Muon and neutron cuts	6552	2679
FV cut	1329	970
Cosmogenic cut	131	55
^{10}C removal	128	55
^{214}Bi removal	119	55
^{208}Tl subtraction	90±13	55±7
^{11}Be subtraction	79±13	47±8
Residual subtraction	75±13	46±8
Final sample	75±13	46±8

Residuals

Background	Rate [10^{-4}cpd/100 t] >3 MeV	>5 MeV
Muons	4.5±0.9	3.5±0.8
Neutrons	0.86±0.01	0
External background	64±2	0.03±0.11
Fast cosmogenic	17±2	13±2
^{10}C	22±2	0
^{214}Bi	1.1±0.4	0

- Inner detector muons can be detected in two ways:
  - Pulse shape (extended tracks have different time profile)
  - Outer detector
- Comparing the two methods gives overall detection efficiency
- 2ms cut after O.D. muons rejects neutrons from water tank

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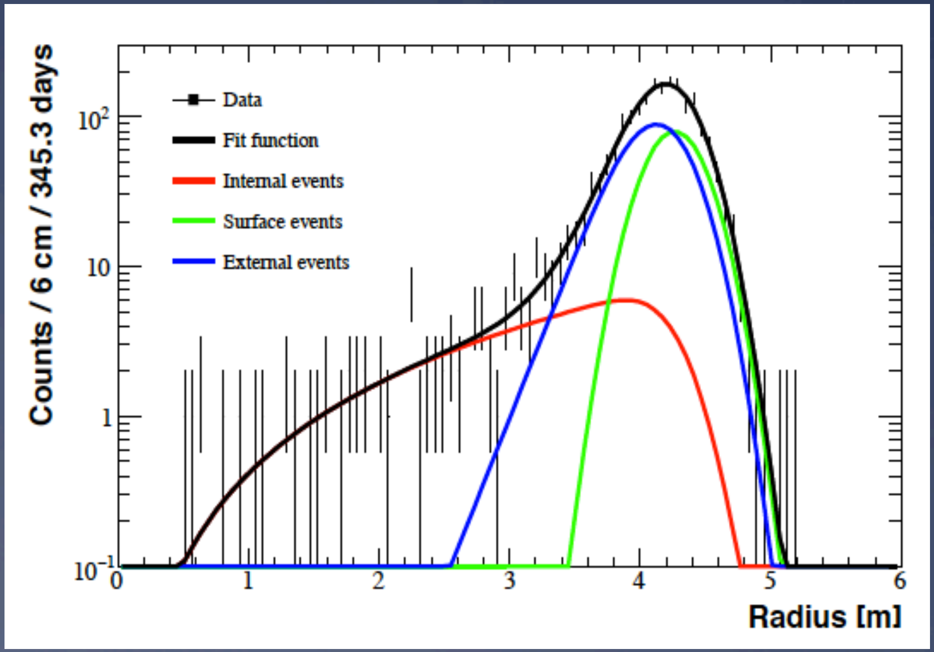
- "Standard" r< 3m, |z| <1.8m fiducial volume
- Contamination estimated from radial profile



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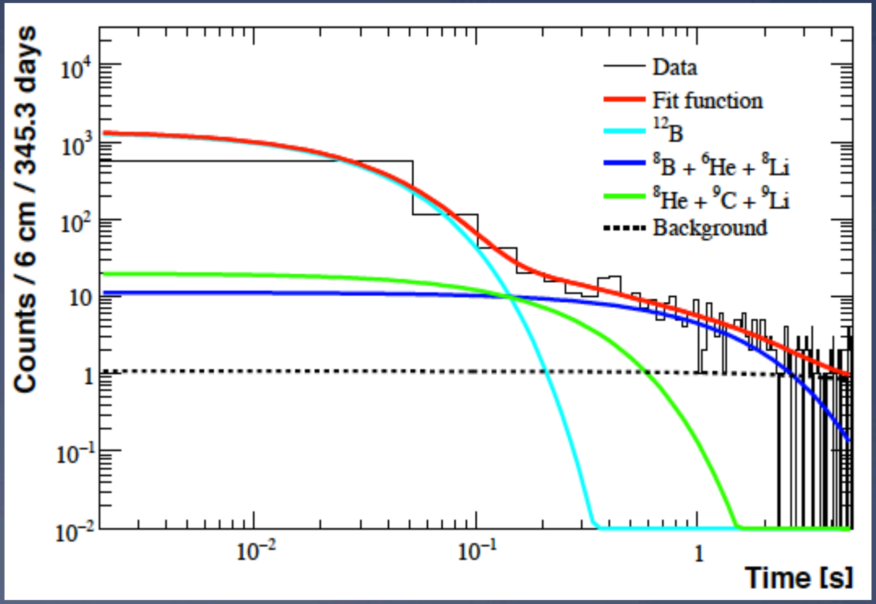
- Fast cosmogenics targeted by 6.5s cut after I.D. muons
  - 29.2% deadtime
- Residual estimated from time profile of events following muons



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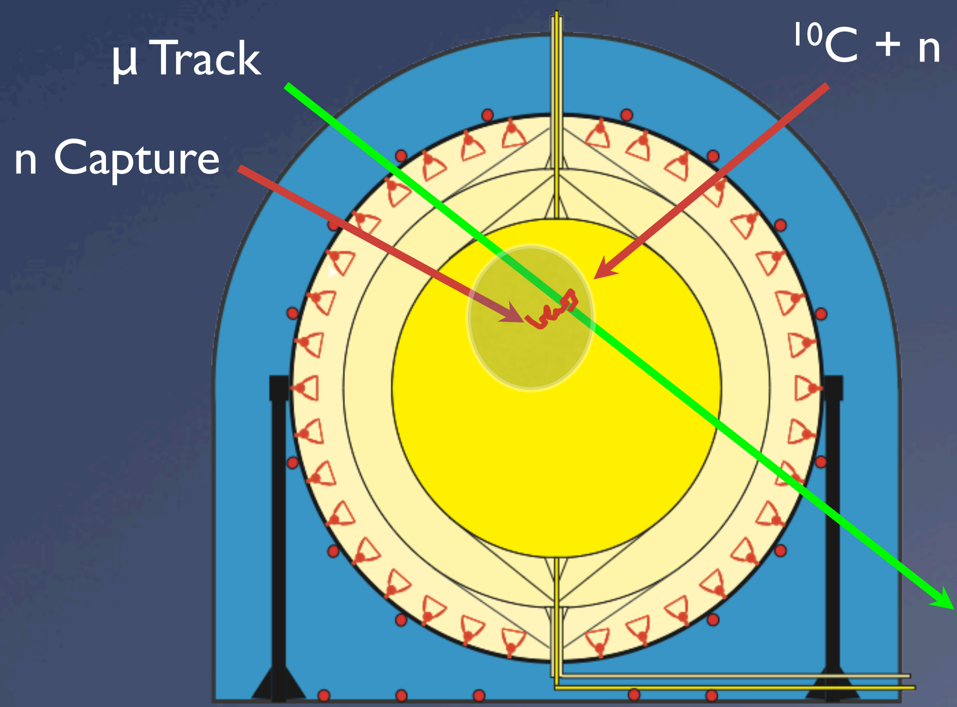
Residuals

Background	Rate [10^{-4}cpd/100 t] >3 MeV	>5 MeV
Muons	4.5±0.9	3.5±0.8
Neutrons	0.86±0.01	0
External background	64±2	0.03±0.11
Fast cosmogenic	17±2	13±2
^{10}C	22±2	0
^{214}Bi	1.1±0.4	0



- ^{10}C has ~30s half-live (too long to veto)
- Often produce via emission of neutron (captures ~250 μs later)

Borexino ^{8}B Analysis

Cut	Counts 3.0–16.3 MeV	Counts 5.0–16.3 MeV
All counts	1932181	1824858
Muon and neutron cuts	6552	2679
FV cut	1329	970
Cosmogenic cut	131	55
^{10}C removal	128	55
^{214}Bi removal	119	55
^{208}Tl subtraction	90±13	55±7
^{11}Be subtraction	79±13	47±8
Residual subtraction	75±13	46±8
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- Neutrons following muons are detected by dedicated flash-ADC DAQ systems triggered by O.D.
  - 94% neutron detection efficiency
  - 67 muon-neutron co-incidences per day
- Veto all events within 85cm of neutron capture point for 120s after muon
  - Cut efficiency 0.7±0.1
- Residual set by inefficiencies + "neutronless" channels $^{12}C(p,t)$ ^{10}C

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- Reject ^{214}Bi using ^{214}Bi-^{214}Po 234 μs delayed coincidence
- Efficiency of 91% (based on the time window used)

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Sum x 345.3 days

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- Subtract ^{208}Tl using rate estimated from ^{212}Bi-^{212}Po 431ns co-incidence (29 ± 7)
- Subtract ^{11}Be using KamLAND production rate scaled (via FLUKA) to Borexino flux and average muon energy
  - Borexino ^{11}Be measurement agrees with scaled value but is less precise
  - Scaling other KamLAND cosmogenic production rates gives good agreement with the observed rates in Borexino

Borexino ^{8}B Flux Result

^{8}B Counting Rate:

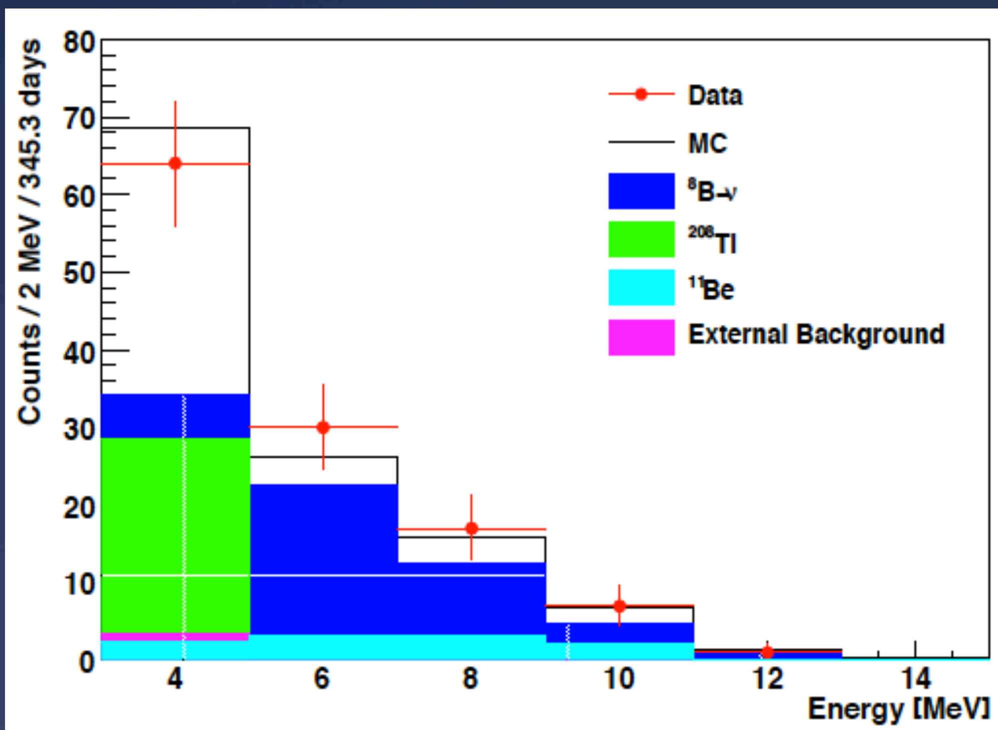
$$0.217 \pm 0.038(stat)^{+0.008}_{-0.008}(syst)\ c/d/100\,t$$ >3MeV

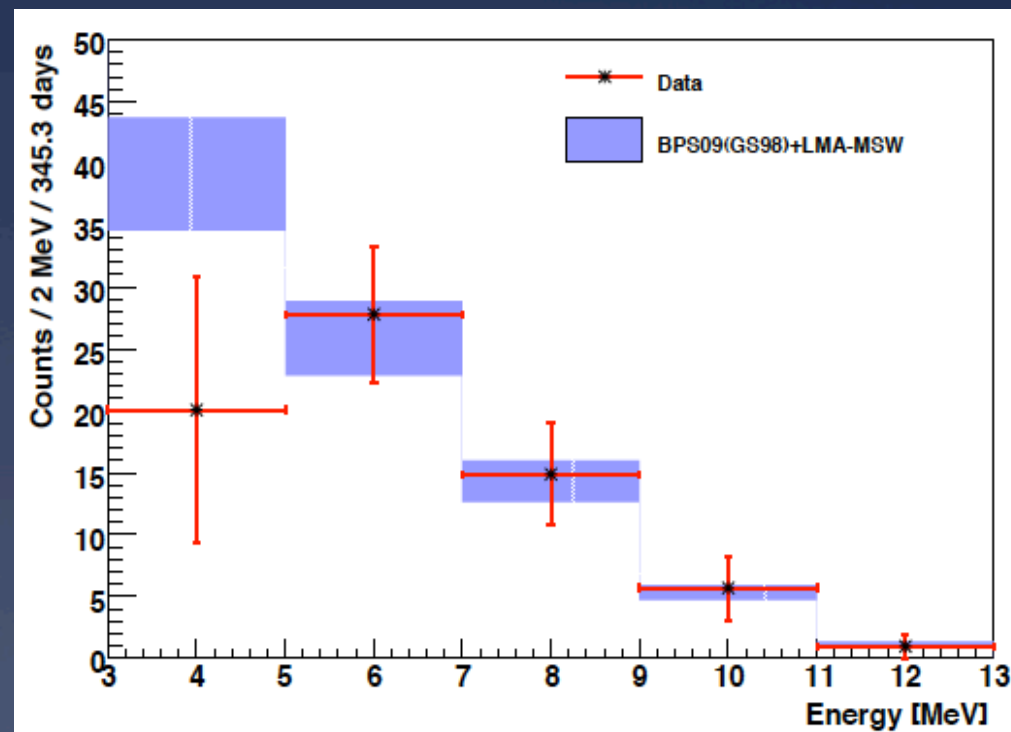
$$0.134 \pm 0.022(stat)^{+0.008}_{-0.007}(syst)\ c/d/100\,t$$ >5MeV

Source	E>3 MeV		E>5 MeV	
	σ_+	σ_-	σ_+	σ_-
Energy threshold	3.6%	3.2%	6.1%	4.8%
Fiducial mass	3.8%	3.8%	3.8%	3.8%
Total	5.2%	5.0%	7.2%	6.1%

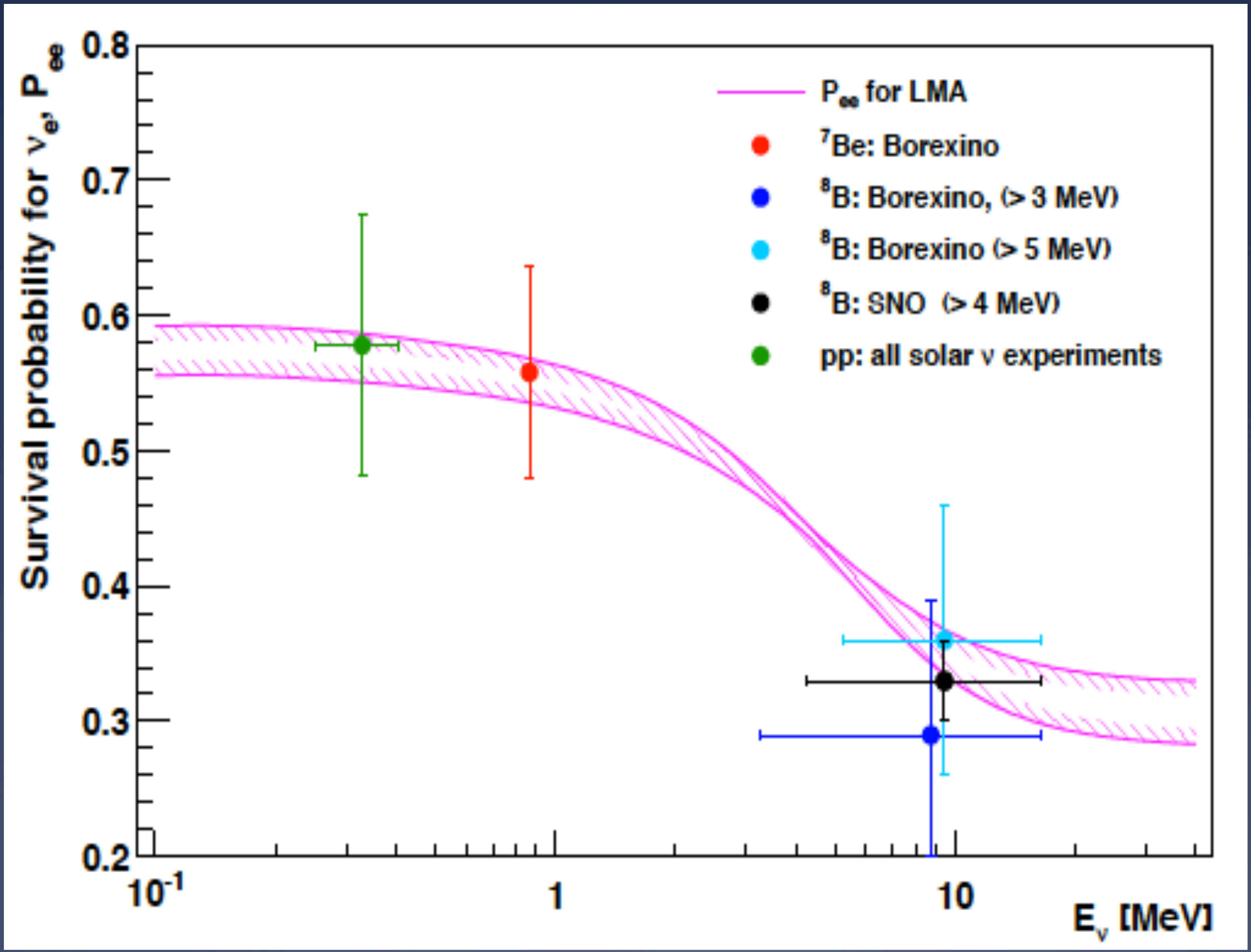
	Threshold [MeV]	$\Phi^{ES}_{^8B}$ [10^6 cm^{-2} s^{-1}]
SuperKamiokaNDE I [7]	5.0	$2.35\pm0.02\pm0.08$
SuperKamiokaNDE II [2]	7.0	$2.38\pm0.05^{+0.16}_{-0.15}$
SNO D_2O [3]	5.0	$2.39^{+0.24}_{-0.23}{}^{+0.12}_{-0.12}$
SNO Salt Phase [26]	5.5	$2.35\pm0.22\pm0.15$
SNO Prop. Counter [27]	6.0	$1.77^{+0.24}_{-0.21}{}^{+0.09}_{-0.10}$
Borexino	3.0	$2.4\pm0.4\pm0.1$
Borexino	5.0	$2.7\pm0.4\pm0.1$

Borexino ^8B Elastic Scattering Spectrum

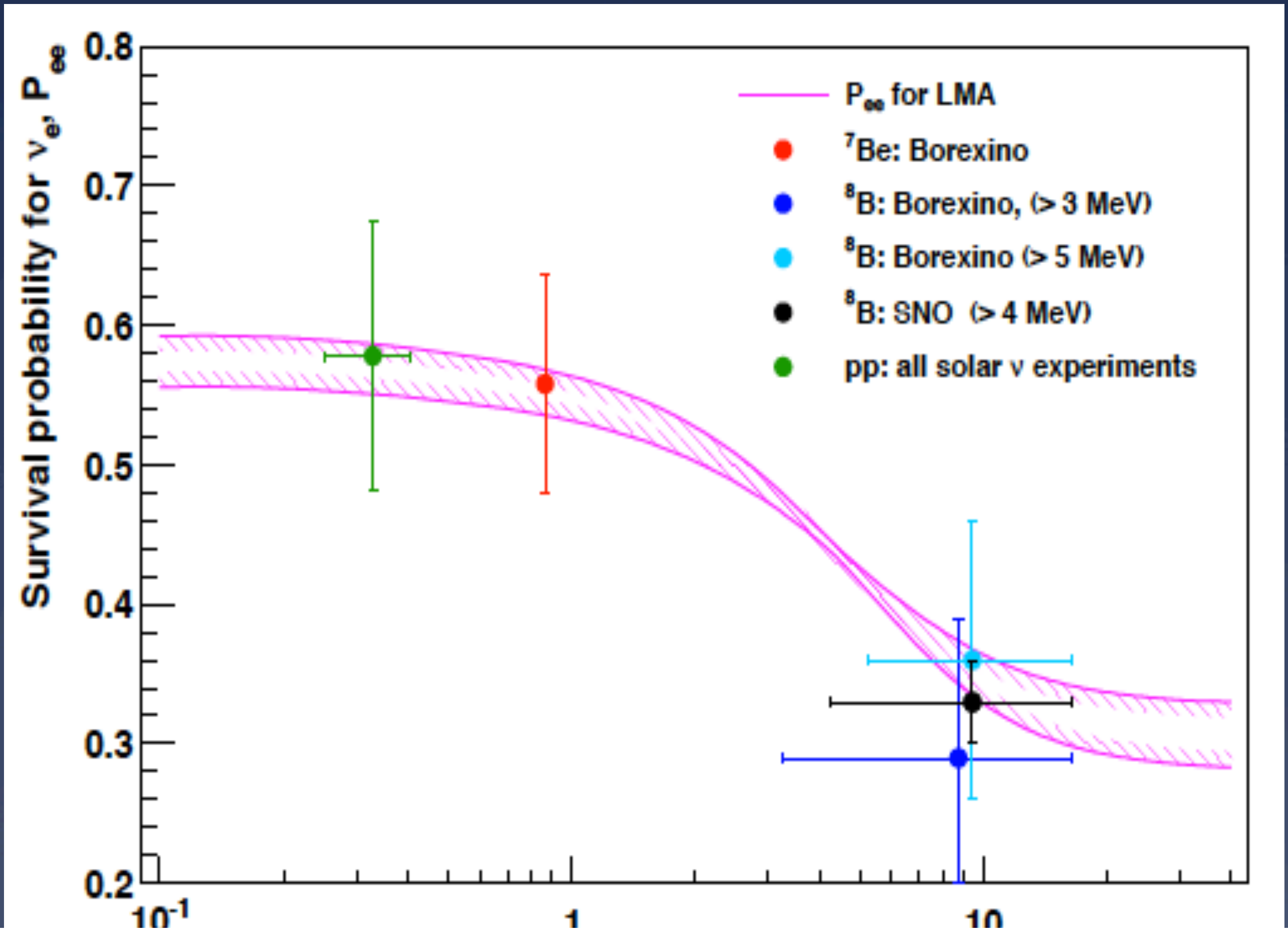




Results on MSW Upturn

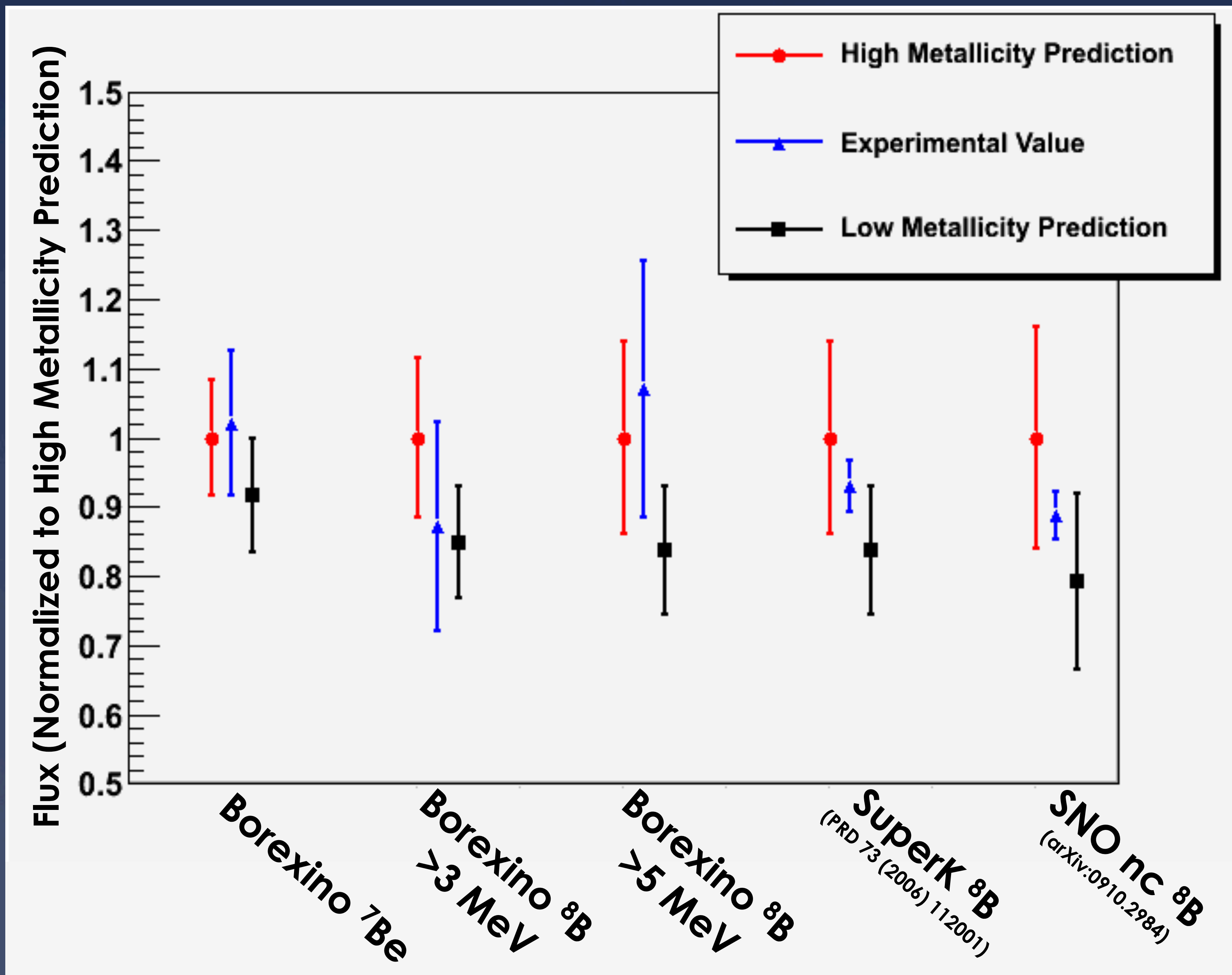


Results on MSW Upturn



Beginning to test MSW predictions with a single experiment: Borexino ^{7}Be and ^{8}B P_{ee}'s differ by 1.9 σ

Solar Metallicity



Geo-Neutrinos

- Antineutrinos from β^- decay of K, U and Th in the earth's mantle and crust
- Models suggest that these decays are responsible for 40-100% of the earth's heat

Not well known!

- Use geoneutrinos to measure the earth's radiogenic heat and chemical composition

Geophysics with neutrinos!

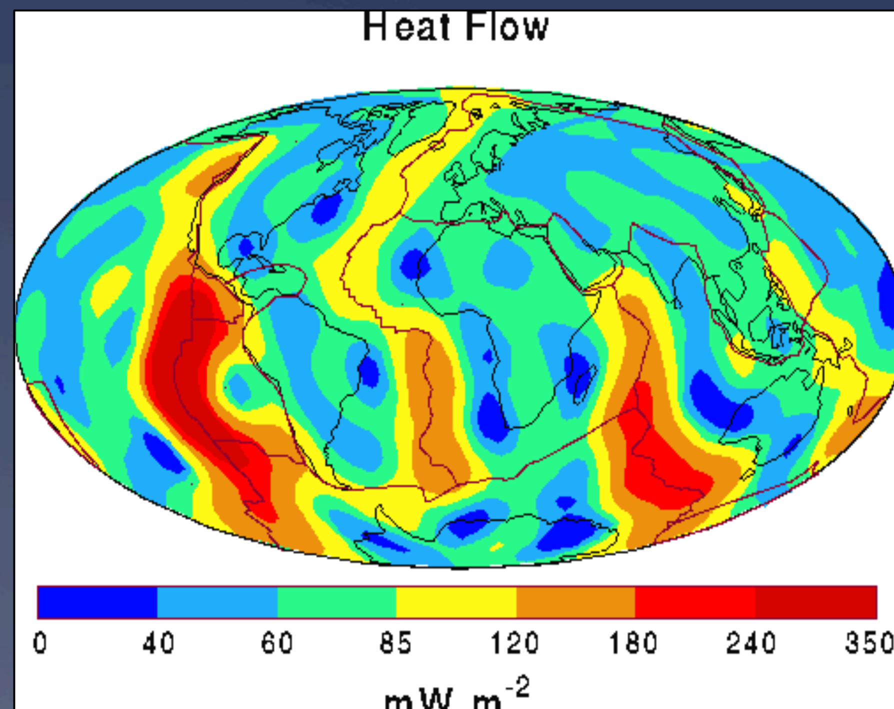
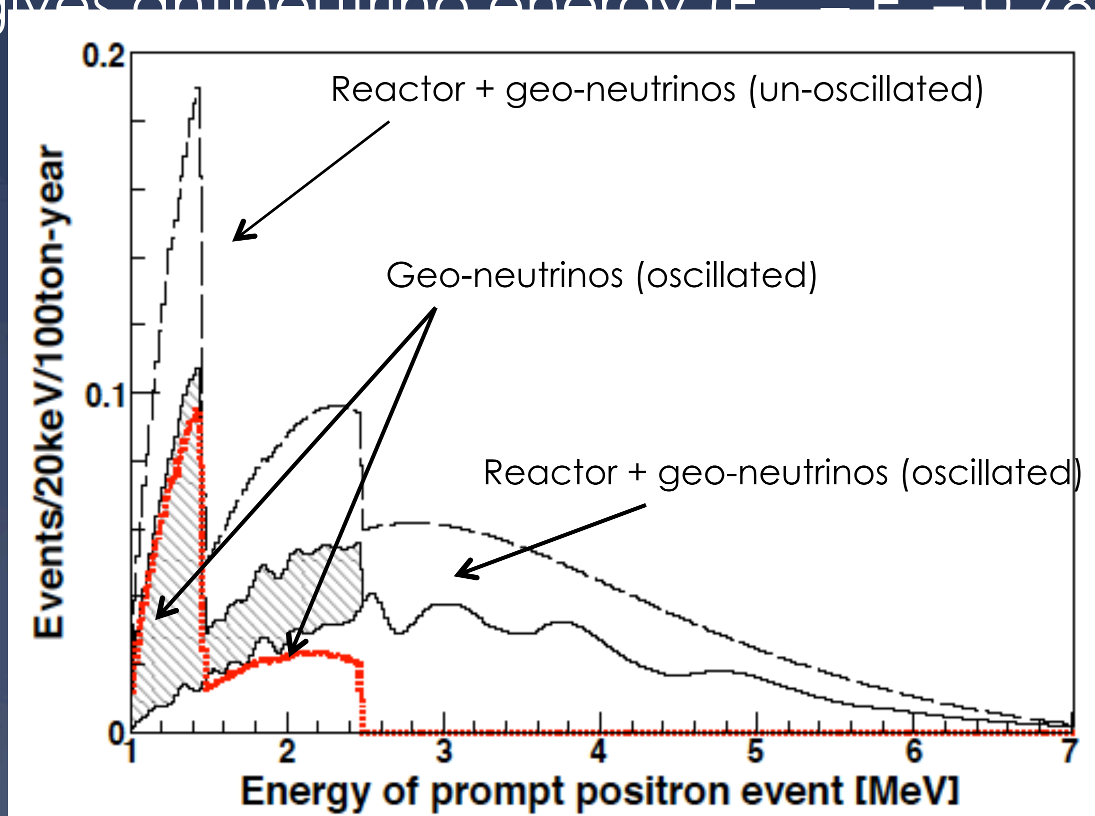


Image from H.N. Pollack, S.J. Hurter and J.R. Johnson, *Reviews of Geophysics* **31**(3), 267-280, 1993

Geo-Neutrinos in Borexino

(PLB687:229 (2010))

- Antineutrino detection via $\bar{\nu}_e + p \rightarrow n + e^+$ (1.8 MeV threshold)
  - Positron gives antineutrino energy (E = E – 0.782 MeV)



Only a handful of events in 100T-yr!

Geo-Neutrinos in Borexino

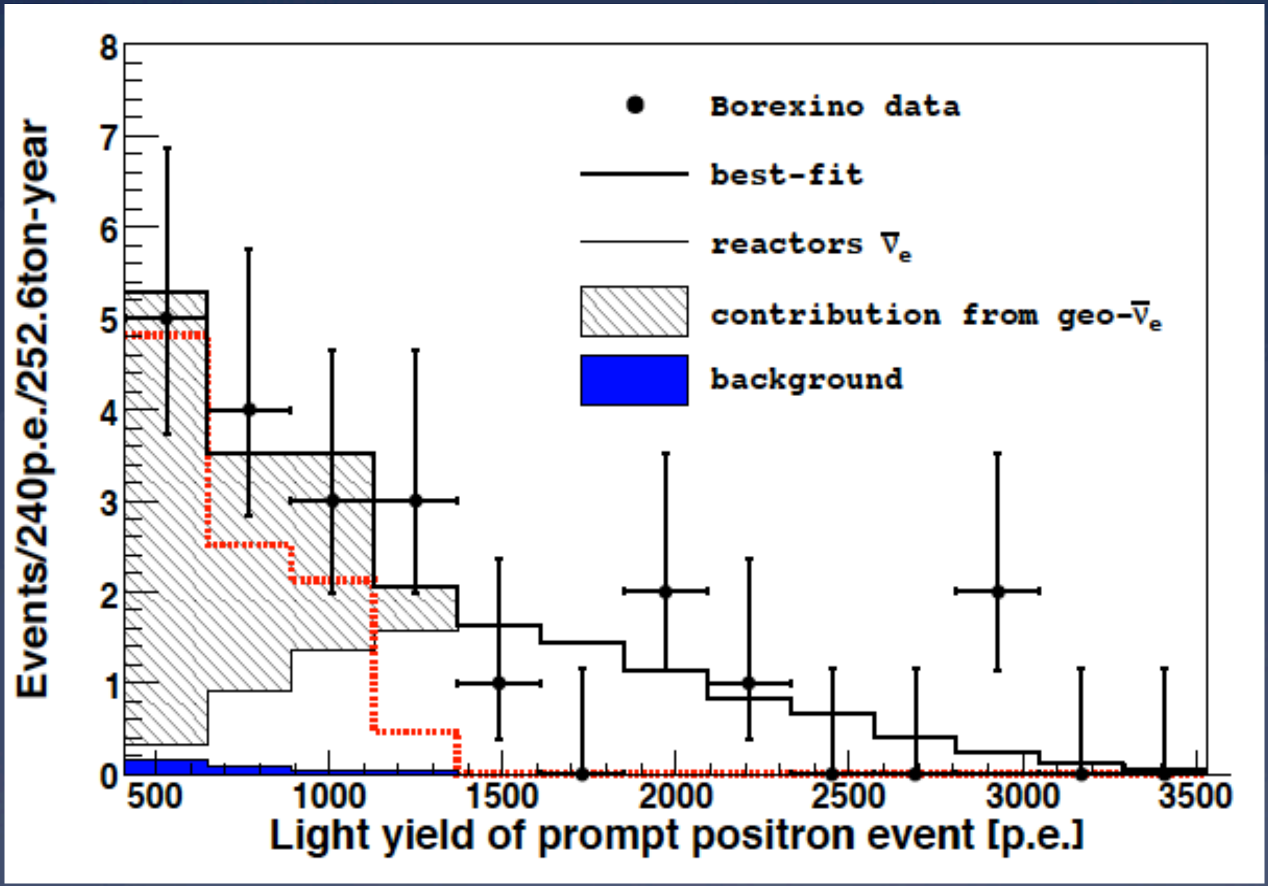
- Powerful background rejection from delayed co-incidence between prompt e^+ and delayed (~256 μ s) n capture

Delayed Co-incidence Backgrounds

Source	Background [events/(100 ton·yr)]
^{9}Li–^{8}He	0.03±0.02
Fast n's (μ's in WT)	<0.01
Fast n's (μ's in rock)	<0.04
Untagged muons	0.011±0.001
Accidental coincidences	0.080±0.001
Time corr. background	<0.026
(γ,n)	<0.003
Spontaneous fission in PMTs	0.0030±0.0003
(α,n) in scintillator	0.014±0.001
(α,n) in the buffer	<0.061
Total	0.14±0.02

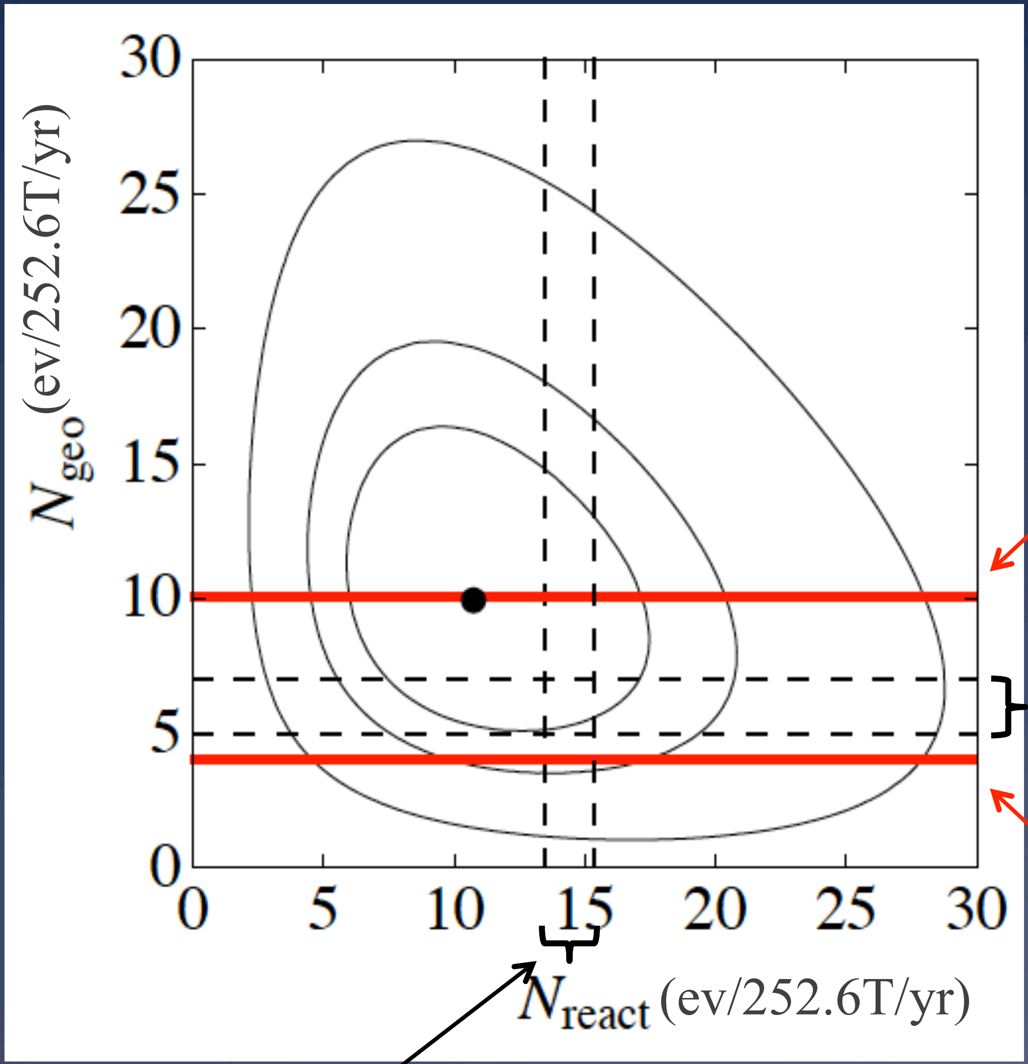
Very low background using almost the full 270T active

Borexino Geo-Neutino Result



Borexino Geo-Neutrino Flux: $3.9^{+1.6}_{-1.3}$ ev/100T/yr

Borexino Geo-Neutino Result



Expectation if entire heat flux from earth's interior is radiogenic.

Range of expectation for "standard" BSE models.

Expectation if all inferred radioactivity is removed.

Reactor neutrino expectation from reactor power outputs.

The Future of Borexino

- Updated ^{7}Be result with higher statistics, reduced systematics
  - Aiming to have a total uncertainty <5%

^{8}B After Calibrations

Source	E>3 MeV		E>5 MeV	
	σ_+	σ_-	σ_+	σ_-
Energy threshold	3.6%	3.2%	6.1%	4.8%
Fiducial mass	3.8%	3.8%	3.8%	3.8%
Total	5.2%	5.0%	7.2%	6.1%

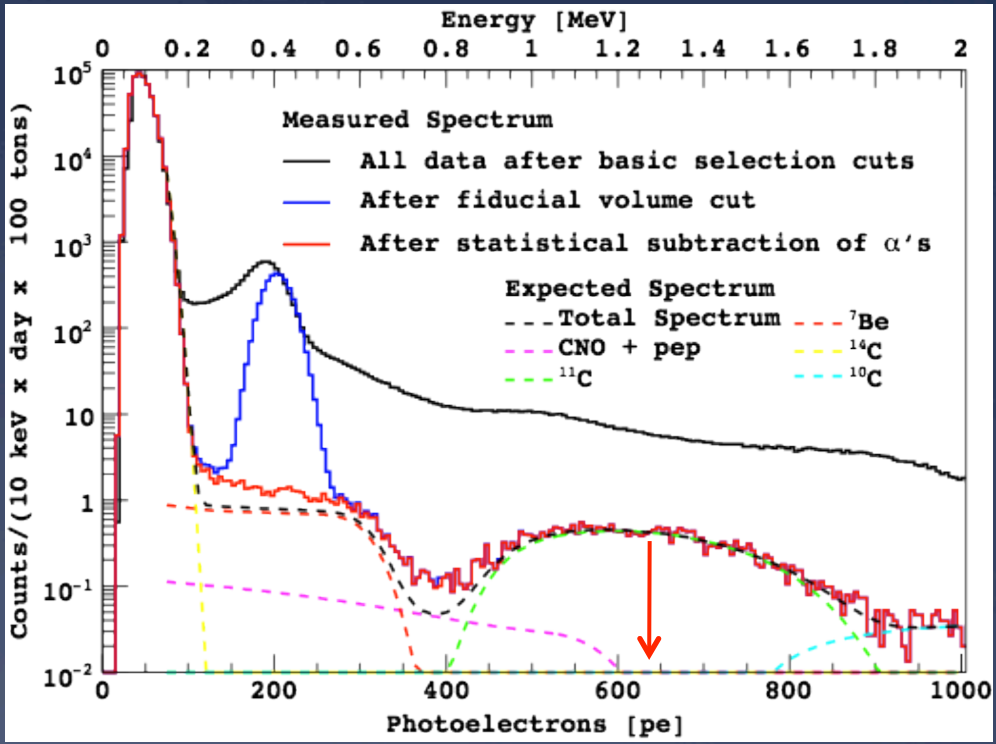
^{7}Be Before Calibration

Fiducial Mass Ratio	6.0
Detector Resp. Function	6.0
	8.5

A 5% ^{7}Be measurement appears to be within reach!

Longer Term

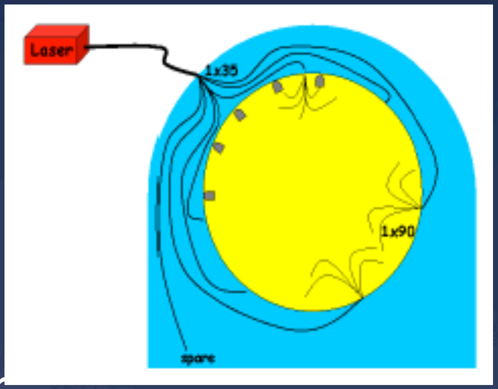
- Re-purification of the scintillator
  - Reduce ^{85}Kr, maybe ^{210}Bi and ^{210}Po
  - Improve the ^{7}Be number even further
- Perhaps other solar neutrino fluxes?
  - The neutron tagging technique that was used on ^{10}C will also work on ^{11}C
  - Pep flux measurement could give high-precision test on SSM + MSW upturn
  - CNO measurement could help constrain solar metallicity
- Continue to accrue statistics for ^{8}B, geo-neutrinos

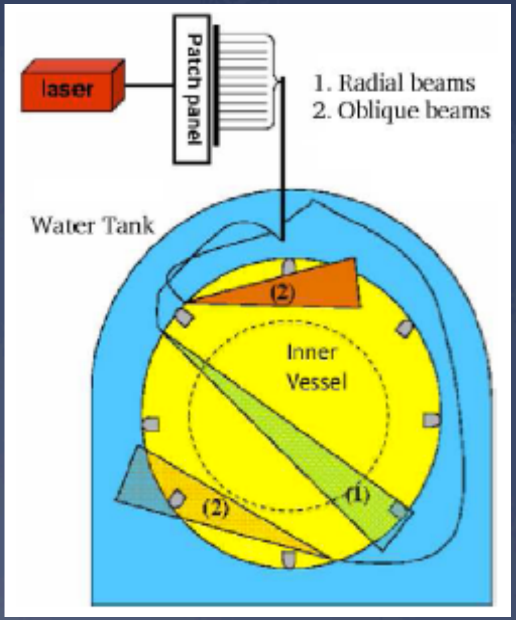


Calibrating the Borexino Detector

Fiber-Based Optical Calibration

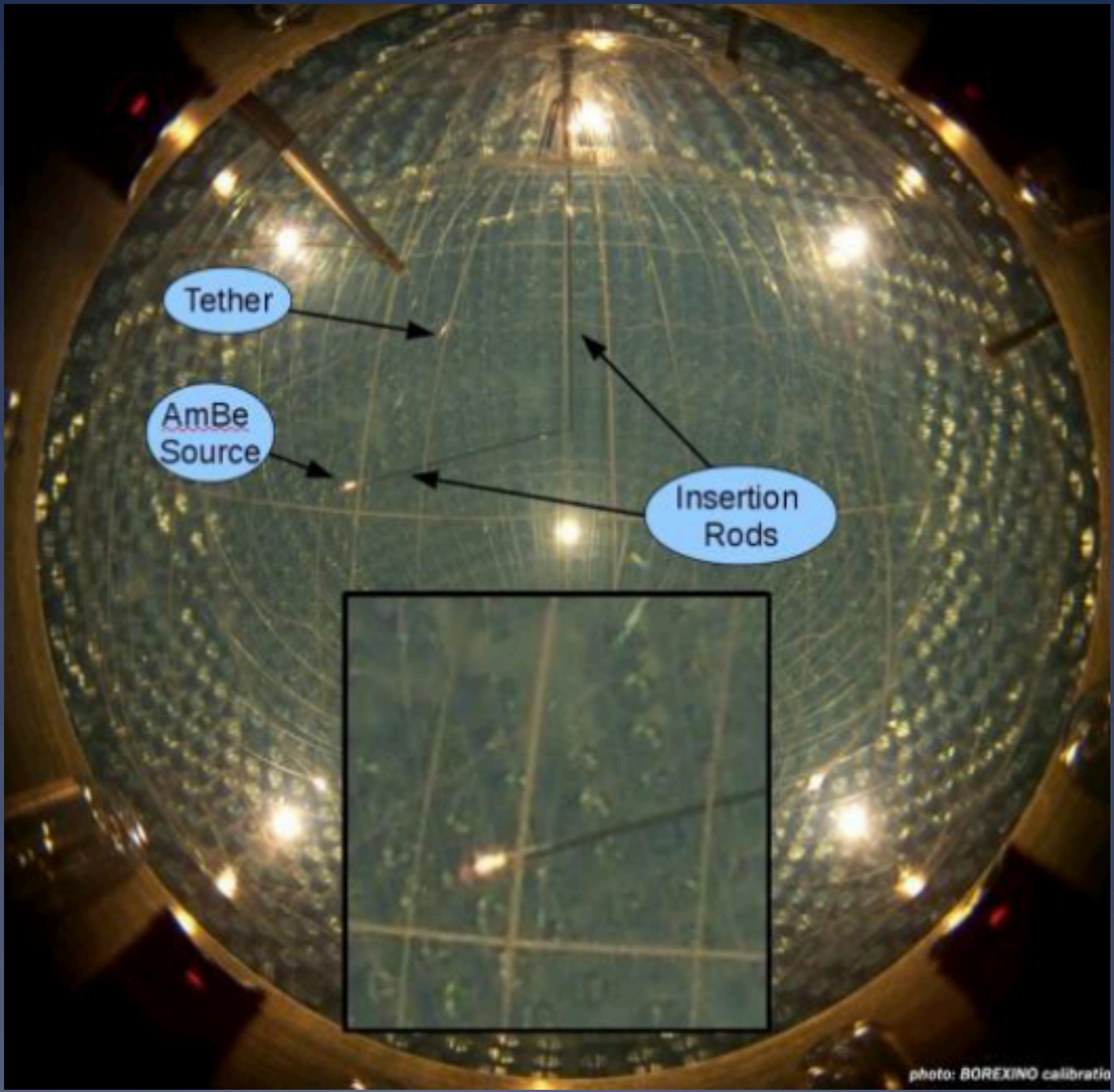
- Optical fibers deliver light to each PMT to monitor gain and measure timing offsets
  - Tubes are pulsed at the beginning of each run as well as during the runs
- Other fibers deliver light across the detector to monitor scintillator optics





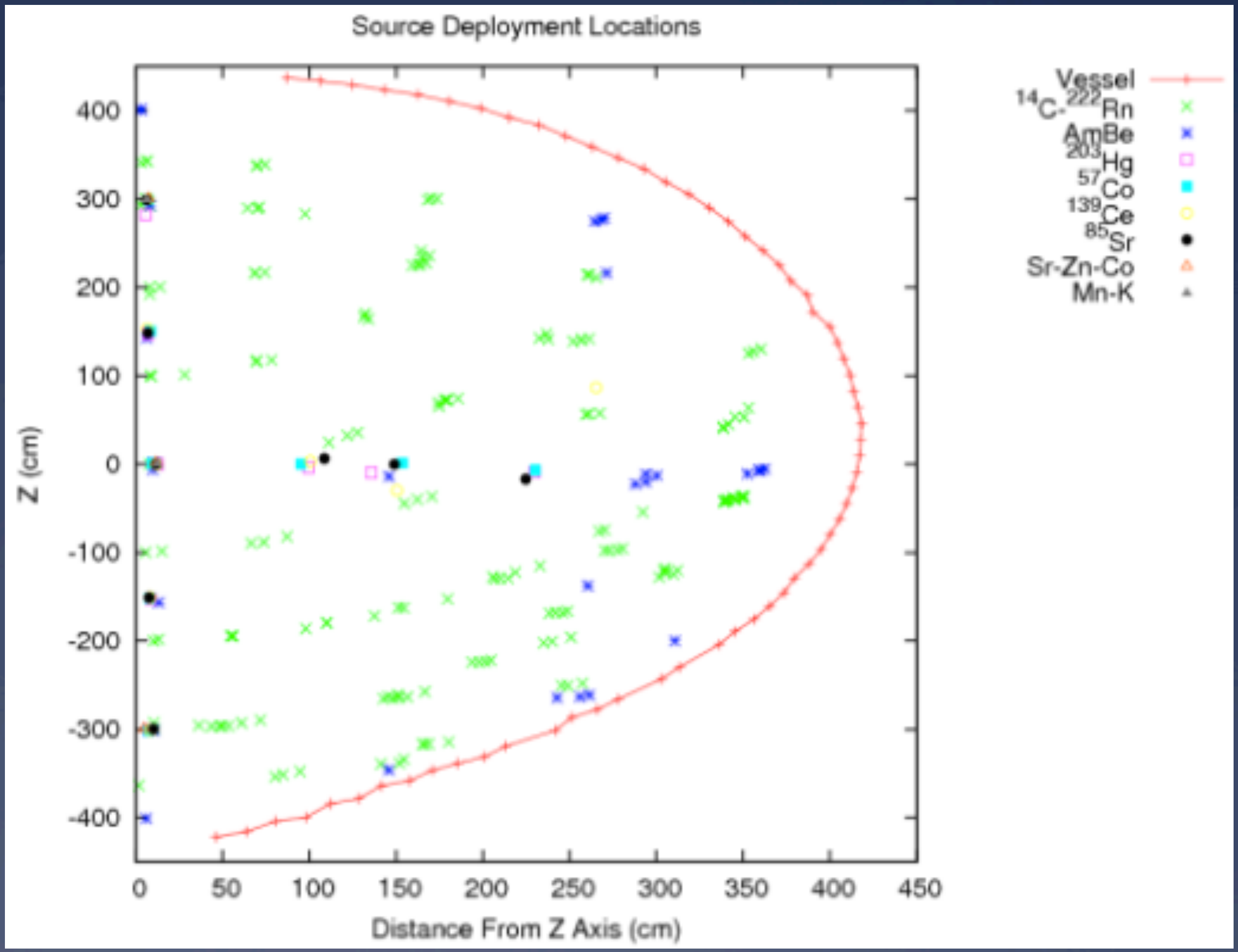
Internal Calibrations

- Radioactive and laser sources deployed throughout the F.V. using stainless steel insertion rods
- Source position known to 2-3cm using a camera-based reconstruction system



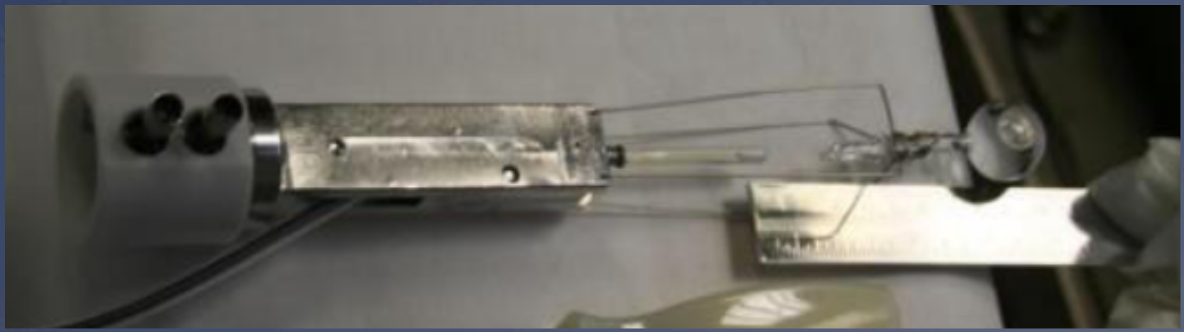
Internal Calibrations

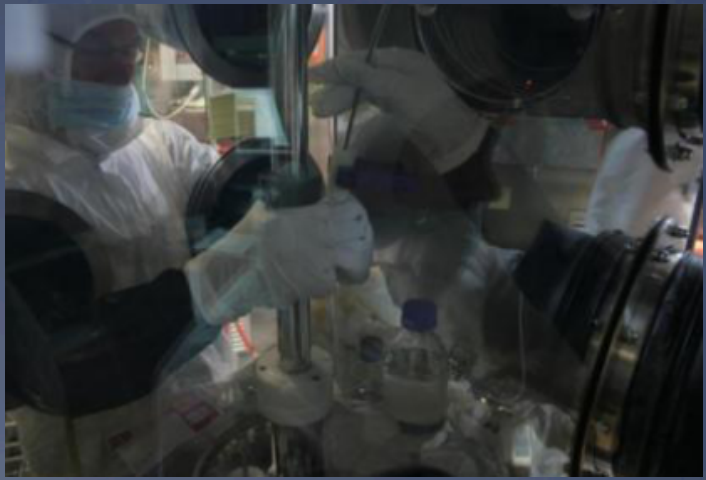
- 4 major calibration campaigns (Oct ’08, Jan ‘09, June ’09, July ’09)
- 35 livedays of calibration data with sources in 295 positions
- Sources:
  - laser diffuser ball
  - AmBe (neutron)
  - ^{222}Rn alpha
  - ^{14}C beta
  - ^{54}Mn, ^{85}Sr, ^{65}Zn, ^{60}Co, ^{203}Hg, ^{40}K, ^{57}Co, ^{139}Ce gamma



Calibration Contamination Control

- Sources flame sealed in quartz vials
- Deployed through a glove-port inside a class 10 clean room
- No significant long term effect on detector backgrounds observed after calibrations





Conclusions

* Extremely low backgrounds achieved by Borexino have allowed re-time measurement of the low energy solar neutrinos
* Beginning to test the solar neutrino survival probability in the "MSW upturn"
* More interesting physics to come

Borexino Collaboration

Astroparticle and Cosmology Laboratory – Paris, France
INFN Laboratori Nazionali del Gran Sasso – Assergi, Italy
INFN e Dipartimento di Fisica dell'Università – Genova, Italy
INFN e Dipartimento di Fisica dell'Università– Milano, Italy
INFN e Dipartimento di Chimica dell'Università – Perugia, Italy
Institute for Nuclear Research – Gatchina, Russia
Institute of Physics, Jagellonian University – Cracow, Poland
Join Institute for Nuclear Research – Dubna, Russia
Kurchatov Institute – Moscow, Russia
Max-Planck Institute fuer Kernphysik – Heidelberg, Germany
Princeton University – Princeton, NJ, USA
Technische Universität – Muenchen, Germany
University of Massachusetts at Amherst, MA, USA
University of Moscow – Moscow, Russia
Virginia Tech – Blacksburg, VA, USA